# AGRONOMIC AND ECONOMIC RESPONSE OF HARD RED WINTER WHEAT TO MULTIPLE LIMING AND FERTILIZATION STRATEGIES

By

ROMULO PISA LOLLATO

Bachelor of Science in Agronomy

Universidade Estadual de Londrina

Londrina, Parana, Brazil

2009

Submitted to the Faculty of the
Department of Plant and Soil Sciences of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2012

AGRONOMIC AND ECONOMIC RESPONSE OF HARD RED WINTER WHEAT TO MULTIPLE LIMING AND FERTILIZATION STRATEGIES

Thesis Approved:

Dr. Jeffrey T. Edwards

Thesis Adviser

Dr. Hailin Zhang

Dr. Francis Epplin

Dr. Sheryl A. Tucker

Dean of the Graduate College

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

# CHAPTER I

## GENERAL INTRODUCTION

Wheat (*Triticum spp.)* is one of the most important cereal crops cultivated in the world. More than 215 million hectares were planted in the 2009-2010 season, with worldwide production of 650 million tons (FAO, 2012). The United States is the third major world producer of wheat, accounting for approximately 60 million tons of wheat from a planted area of around 20 to 25 million hectares (FAO, 2012). Most of the wheat grown in the U.S. is winter wheat (*Triticum aestivum* L.), and the Great Plains is the region where most of the U.S. winter wheat is grown. In the 2011-2012 winter wheat production season, for example, 16.9 million hectares were planted to winter wheat in the country, and 65% of that total, 10.9 million hectares, was planted in the seven-state region of the Great Plains including Colorado, Kansas, Nebraska, Oklahoma, South Dakota, Texas, and Wyoming (USDA, 2012).

Hard red winter wheat is the most broadly cultivated crop in Oklahoma (USDA, 2010), and is a critical component of Oklahoma farm income. Approximately 2.3 to 2.6 million hectares are sown to winter wheat every year in the State, representing around 20% of the total winter wheat planted within the Great Plains (NASS, 2012a). Thus, elucidation and refinement of management practices that optimize winter wheat yield, such as fertilization, pest and disease management, and soil acidity correction, are crucial for farming systems in Oklahoma.

Most Oklahoma soils are naturally productive due to their process of formation, and thus acidity was not a recurring problem prior to cultivation; however, man's activities and intense agricultural production resulted in lower productivity of some of these soils (Zhang and Raun, 2006). Soil pH of 5.5 is considered to be the threshold at which pH can limit wheat productivity, and data derived from the OSU soil-testing program indicates that the acidity of many wheat fields in the State are below this threshold. The number of fields in which acidity may be limiting wheat production increased between the years of 1985 and 1996. More than 30% of Oklahoma's fields cropped to continuous wheat were estimated to have pH lower than 5.5 in 1985 (Johnson et al., 1991), and by 1996 this number had increased to 39% (Zhang et al., 1998a). This problem has not improved in recent years. Zhang and McCray (2009) found that the proportion of samples from the wheat growing region of the state with pH < 5.5 was 40 %.

In western Oklahoma, the primary wheat production area, continuous use of ammonium-based fertilizers is most likely the primary cause for the accelerated acidification of soils due to a net hydrogen ion (H) release during nitrification (Bohn et al., 2001; Nye, 1981). Besides H release, when nitrate ($NO_3$) is not taken up by the crop it moves downward with soil water, reacts with positively charged nutrients such as Ca and Mg, and leaches which further acidifies the soil (Spies and Harms, 2007). The continuous harvest of crops may also have increased soil acidity (Johnson and Zhang, 2009), as crops uptake alkaline elements for their general nutrition and these elements are removed with grain and forage harvested.

Several factors can limit crop production in acid soils. Soil acidity constrains plant development by reduced root growth (Marschner, 1991). Greater availability of metals including H, Al and Mn, can result in plant toxicity, and soil deficiencies of several essential mineral elements such as N, P, K, Ca, and Mg can take place due to lower nutrient availability at low pH (Fageria and Zimmermann, 1998; Kochian et al., 2004). In acid soil conditions the occurrence of suboptimal levels of phosphorus (P) is considered a primary limitation to crop production. The availability of soil phosphate in soil solution is highly pH dependent, and the precipitation of insoluble Al, Mg, and Fe phosphates is the main mechanism for phosphate fixation under acid conditions, decreasing P availability (Bohn et al, 2001; Fageria and Stone, 2006; Haynes, 1982).

In Oklahoma, Al toxicity is the major cause of crop failure in extreme acid soils (Boman et al., 1992). The first symptom of Al toxicity is a rapid inhibition of root growth, resulting in a reduced capacity of the root system to explore soil for moisture and nutrients that limits water and mineral nutrient uptake (Kochian et al., 2004; Lidon et al., 2000; Tang et al., 2002). Reduced root growth results in reduced aboveground biomass and leaf area index of wheat, consequently decreasing cumulative intercepted radiation and subsequent grain yield (Valle et al., 2009).

The most widely used long-term method for soil acidity amelioration is application of agricultural lime to raise soil pH. Lime application rate is based on the soil buffer index, and field trials have demonstrated its effectiveness to correct soil acidity over time and to eliminate the adverse effects of low pH soils (Curtin and Syers, 2001; Ernani et al., 2002; Haynes, 1982; Kaitibie et al., 2002; Kariuki et al., 2007; Liu et al., 2004; Tang et al., 2002; Zhang et al, 1998a). Several studies indicate a significant increase in wheat grain yield due to lime application (Coventry et al., 1987; Kaitibie et al., 2002; Scott et al., 2001; Tang et al., 2002); however, Boman et al. (1993) found no differences in wheat yield between limed and non-limed plots. Coventry et al. (1987) observed a trend of lower yields and accentuated root disease when lime was applied at 5.0 Mg $ha^{-1}$, compared to the 1.0 Mg $ha^{-1}$ lime treatment. The correlation between higher lime rates and consequently higher soil pH with soilborne cereal diseases, such as take-all (*Gaeumannomyces graminis* var. *tritici*) and root-rot (*Rhizoctonia solani*), is well reported and believed to be a constraint to wheat yields grown in high pH soils (Christensen et al., 1987; MacNish, 1988; Smiley and Cook, 1973).

When evaluating the economic aspects of lime application, it is important to consider the residual effect of liming because of its carry-over effect (Lukin and Epplin, 2003). Kaitibie et al. (2002) found that pre-season lime application combined with banded phosphorus, was the most favorable strategy for dual-purpose wheat production when lime costs were amortized over a five-year period. Still, lime was not economically justifiable if the entire cost of lime application had to be recovered the year of application. For this reason, many producers choose to address low soil pH in continuous wheat production by applying banded P fertilizer with the seed to reduce Al toxicity and increase P availability (Guertal and Westerman, 1992; Zhang et al., 1998a). Kaitibie et al. (2002) found that P fertilizer applied in furrow significantly increased wheat grain yield in low pH soils, and was the most suitable economic strategy when lime costs were fully assessed in the year of application. The banding of P on acid soil has been shown to benefit wheat yield by reducing Al toxicity in the vicinity of the plant roots and providing readily-available P to the crop (Johnson et at., 1991; Zhang et al., 2010). Faster P fertilizer access by the root early season stimulates tillering and head formation on winter wheat, thus increasing grain yield (Sander and Eghball, 1999).

Pelletized lime is sometimes used as an alternative to agricultural lime to address low soil pH (Spies and Harms, 2007; Zhang et al, 2010). Pelletized lime contains the same lime material as ground limestone, but to avoid dust problems with the very fine particles of this form and to increase ease of handle, powdered limestone is compressed into granules using lignosulfates as pelletizing agents (Murdock, 1997; Staton and Warncke, 2006). Pelletized lime is frequently marketed to farmers as a low-use-rate, quick fix for low soil pH; however, broadcast pelletized lime is no more efficient than broadcast lime of the same ECCE (Staton and Warncke, 2006; Zhang et al., 2010). When used at recommended rates, pelletized lime can have prohibitive costs because it is 4 or 5 times more expensive then agricultural lime (Zhang et al., 2010, Staton and Warncke, 2006). Similar to P, some producers have considered banding 200 or 400 kg ha$^{-1}$ of pelletized lime as a low-cost alternative to broadcast applications. While research on this practice is limited, published studies from Ohio have shown the use of pelletized lime at quantities less than the lime requirement did not neutralize soil acidity to desired levels (Lentz et al., 2010).

Given the importance of wheat to the Oklahoma agricultural economy and changing prices for agricultural inputs and grain crops, reevaluation of extension recommendations for amelioration of low soil pH is warranted. The objectives of this research were: (i) assess the effects of broadcast agricultural lime, banded pelletized lime, and banded phosphorus fertilizer on soil chemical characteristics and hard red winter wheat vegetative development and grain yield; (ii) evaluate the spatial distribution of pH change from broadcast agricultural lime and banded pelletized lime; and (iii) determine the economic optimal strategy for soil acidity amelioration for grain-only wheat production in Oklahoma.

ABSTRACT

Application of agricultural lime is the most frequently recommended method for managing low soil pH; however, in-furrow phosphorus (P) fertilizer or pelletized lime are also commonly used to ameliorate soil acidity. The objectives of this study were to evaluate three soil acidity amendment strategies for winter wheat production. The effects of broadcast agricultural lime (2.25 or 4.50 Mg ECCE $ha^{-1}$), banded pelletized lime (225 or 450 kg $ha^{-1}$ $yr^{-1}$), and banded P fertilizer (28 or 56 kg $ha^{-1}$ $yr^{-1}$) on bulk soil pH, aluminum saturation ($Al_{sat}$), pH change in the soil profile, wheat vegetative development, plant population uniformity, and grain yield, were investigated during three growing seasons in a Grandfield Fine Sandy Loam and a Grant Silt Loam with initial soil pH of 4.8 and 4.9 at Altus and Waukomis, OK. Broadcast agricultural lime at 4.50 Mg $ha^{-1}$ increased soil pH by one unit and decreased $Al_{sat}$ by 98% at Waukomis. Neither banded pelletized lime nor P fertilizer affected these parameters in either location. Changes in soil pH caused by banded pelletized lime were restricted to the region surrounding the pellet, while broadcast agricultural lime increased soil pH throughout the profile. In-furrow P fertilizer increased vegetative growth and plant population homogeneity in all years of the study at Waukomis; broadcast lime provided similar results in 2010-11 when low soil pH effects on crop growth were more apparent due to severe drought. Wheat grain yield was not affected by treatment, probably due to low soil $Al_{sat}$. When broadcast lime costs were amortized over five years, 2.25 Mg ECCE $ha^{-1}$ and the control resulted in the highest net returns among treatments. Results indicate that banded P fertilizer or broadcast agricultural lime can increase early-season wheat growth and population uniformity in a low-pH soil, but this increase in vegetative growth might not result grain yields significantly higher than the control when $Al_{sat}$ is lower than 10%.

# CHAPTER II

# REVIEW OF LITERATURE

Acid soils are a limitation to crop production throughout the world. According to von Uexküll and Mutert (1995), more than 30% of world land area is characterized by soil pH < 5.5, critical level below which aluminum (Al) availability is increased and crop grain yields can be decreased (Kariuki et al., 2007; Schroder et al., 2011; Valle et al., 2009). Although acidity was not a recurring problem in most Oklahoma soils due to their process of formation, intense agricultural production and continuous use of nitrogen fertilizer resulted in decreased soil pH in many Oklahoma soils (Zhang and Raun, 2006). An extensive survey conducted between 1994 and 1999 indicated that up to 39% of the fields in the central wheat growing region of Oklahoma had pH < 5.5 (Zhang, 2001), and there is no indication that pH levels have improved since the survey was conducted. Soil pH per se rarely affects plant growth directly (von Uexktill and Mutert, 1995); however, Al toxicity has become a major cause of crop failure or yield reduction in the southern region of the Great Plains (Zhang and Raun, 2006).

Hard red winter wheat is a critical component of Oklahoma's farm income as it is the most broadly cultivated crop in the State, with a total of approximately 2.3 to 2.6 million hectares planted every year (NASS, 2012a). In Oklahoma, Al toxicity is the major cause of crop failure in extreme acid soils (Boman et al., 1992). Wheat responses to Al toxicity are typically inhibition of root growth resulting in a reduced capacity of the root system to explore soil for moisture and nutrients that limits water and mineral nutrient uptake (Lidon et al., 2000; Kochian et al., 2004; Tang et al., 2002). Reduced root growth results in reduced aboveground biomass and forage production (Kaitibie et al., 2002; Kariuki et al., 2007), leaf area index, and, consequently, reduced cumulative intercepted radiation and grain yield (Valle et al., 2009). Wheat sensitivities to soil pH and Al are cultivar specific and forage production seems to be more affected by Al than grain yield (Kariuki et al., 2007; Valle et al., 2009).

If the soil holds adequate levels of base cations, the presence of potassium chloride extractable Al ($Al_{KCl}$) may not induce Al toxicity symptoms in the crop (Johnson et al., 1997; Kariuki et al., 2007). Hence, a more consistent indicator of Al toxicity potential is the Al saturation ($Al_{sat}$), a measure of Al concentration expressed as a percentage of total exchangeable base cations (i.e. Ca, Mg, and K) of the soil (Sumner and Miller, 1996). Due to the inherent differences in soil chemical properties in the Great Plains, fields with analogous soil pH can result in very dissimilar values of Al saturation (Johnson et al., 1997), affecting wheat grain yield in different ways (Kariuki et al., 2007; Schroder et al., 2011; Wise, 2002).

Application of agricultural lime is the most frequently recommended method for managing low pH and high $Al_{KCl}$ and $Al_{sat}$ soils, and its effectiveness is well documented (Curtin and Syers, 2001; Ernani et al., 2002; Kaitibie et al., 2002; Liu et al., 2004; Tang et al., 2002; Zhang et al, 1998a; Haynes, 1982). Although ground limestone is the suggested technique for soil acidity amelioration in wheat production systems of Oklahoma (Zhang and Raun, 2006), its application does not always results in increased wheat grain yield (Boman et al., 1993; Caires et al., 2002; Caires et al., 2005; Liu et al., 2004; Scott et al., 2001) and can increase the pressure of soilborne diseases (Christensen et al., 1987; MacNish, 1988; Smiley and Cook, 1973). Economics of liming, either due to large amounts required or transportation costs, sometimes makes producers reluctant when applying lime to overcome low soil pH (Ruiz-Torres et al., 1992; Samac and Tesfaye, 2003).

When evaluating the economic aspects of lime application, it is important to consider the residual effect of liming (Lukin and Epplin, 2003). Kaitibie et al. (2002) found that pre-season lime application combined with banded phosphate fertilizer was the most favorable strategy for dual-purpose wheat production when lime costs were amortized over a five-year period. Still, lime was not economically justifiable if the entire cost of lime application had to be recovered the year of application. In-furrow P fertilizer is a suitable economic strategy for dual-purpose wheat in acid soils especially when lime costs need to be fully assessed in the year of application (Kaitibie et al., 2002). For this reason, many producers choose to address low soil pH in continuous wheat production by applying banded P fertilizer with the seed to reduce Al toxicity and increase P availability (Guertal and Westerman, 1992; Zhang et al., 1998a).

In extremely acid soils, Al can react with soil phosphorus (P), turning it insoluble and unavailable for plant uptake; consequently, suboptimal levels of P can become a primary limitation to crop production (Fageria and Stone, 2006; Kochian et al., 2004). The banding of P on acid soils has been shown to benefit wheat yield by reducing metal toxicity in the vicinity of the plant roots and providing readily-available P to the crop (Johnson et at., 1991; Sloan et al., 1995). Faster early-season P fertilizer access by the root stimulates tillering (Rodríguez et al., 1998; Rodríguez et al., 1999; Sato et al., 1996) and greater aboveground biomass production, which will increase cumulative intercepted radiation (Sandaña and Pinochet, 2011; Sandaña et al., 2012), and possibly result in increased grain yield (Sander and Eghball, 1999).

Pelletized lime is sometimes used as an alternative to agricultural lime to address low soil pH (Spies and Harms, 2007; Zhang et al, 2010). Pelletized lime contains finely ground limestone compressed into granules, which allows the even and accurate distribution of the material and avoids dust problems (Higgins et al., 2012; Murdock, 1997; Staton and Warncke, 2006). Pelletizing agents used to bind the fine limestone are generally clay or synthetic binders (lignosulfates), which dissolves in contact with rainfall or soil solution (Higgins et al., 2012). The binding agent, however, is critical in determining the reaction rate of pelletized lime (Lentz et al., 2010). Pierce and Warncke (2000) found that pelletized lime was slow to react in the field, and further laboratory incubation confirmed that it reacted much slower than agricultural lime. They attributed the slow reaction time to the lignosulfate binding agent used in the granulation process, which probably retarded the dissolution of the pellet. Pierce and Warncke (2000) also postulated that the large granules of lime came in contact with less soil than agricultural lime, which would slow the soil pH correction rate relative to that of agricultural lime. Slower rate of reaction of pelletized lime when compared to agricultural lime was also reported by Murdock (1997) and Ingram and Johnson (1982).

Pelletized lime is frequently marketed as a low-use-rate, quick fix for low soil pH; however, broadcast pelletized lime is not more efficient than broadcasted lime when applied at similar quantities (Godsey et al., 2007; Higgins et al., 2012). When used at recommended rates, pelletized lime can have prohibitive costs because it is 4 or 5 times more expensive than agricultural lime (Staton and Warncke, 2006; Zhang et al., 2010). Thus, pelletized lime is proposed as a maintenance product to be applied yearly at 350 kg $ha^{-1}$ $yr^{-1}$ (Higgins et al., 2012). Some producers have considered banding 200 or 400 kg $ha^{-1}$ $yr^{-1}$ of pelletized lime as a low-cost alternative to broadcast applications, similar to in-furrow P application. While research on this practice is limited, published studies have shown the use of pelletized lime at quantities less than the lime requirement did not neutralize soil acidity to desired levels and resulted in only slight changes in soil pH (Higgins et al., 2012; Lentz et al., 2010).

Given the importance of wheat to the Oklahoma agricultural economy and the limited amount of data on the effectiveness of banded pelletized lime, the objectives of this study were to

(i) assess the effects of broadcast agricultural lime, banded pelletized lime, and banded phosphate fertilizer on soil chemical composition and hard red winter wheat vegetative development and grain yield, (ii) evaluate spatial distribution of pH change from broadcast agricultural lime and banded pelletized lime, and (iii) determine the economic optimal strategy for soil acidity amendment for grain-only wheat production in Oklahoma.

# CHAPTER III

# METHODOLOGY

### *3.1. Locations and Soils*

The study was conducted over a three-year period at two different locations in the State of Oklahoma. The first site, near Altus (34° 38' 17" N, 99° 20' 1" W), was initiated during the 2008-2009 winter wheat production season in a Grandfield Fine Sandy Loam (fine-loamy, mixed, superactive, thermic Typic Haplustalfs) with initial soil pH of 4.8. Initial Mehlich-3 P on the study site was 86.5 ppm, which is reported as a 100% sufficiency level for grain production according to Oklahoma State University extension recommendations (Zhang et al., 1998b). The Altus site was terminated following the 2010-2011 wheat production season. A second site was added near Waukomis (36° 16' 49" N, 97° 53' 53" W) during the 2009-2010 season and was maintained until the 2011-2012 season in a Grant Silt Loam (fine-silty, mixed, superactive, thermic Udic Argiustolls), with initial pH of 4.9 and soil P test of 23.5 ppm, or 93% sufficiency.

### *3.2. Experimental Design*

A randomized complete block design with seven treatments and four replications was used. Treatments included a control plot receiving no soil acidity amendment strategy; ground agricultural lime at 2.25 or 4.50 Mg ha$^{-1}$ effective calcium carbonate equivalent (ECCE); in-furrow pelletized lime at 225 kg $ha^{-1}$ $yr^{-1}$ or 450 kg $ha^{-1}$ $yr^{-1}$; or in-furrow triple superphosphate (TSP, 0-46-0) at 28 kg $ha^{-1}$ $yr^{-1}$ or 56 kg $ha^{-1}$ $yr^{-1}$. Plots were 5.2 meters long and consisted of eight 15-cm rows for a total width of 1.2 meters. The cultivar Fuller (Fritz et al., 2007), which is sensitive to low soil pH and moderately sensitive to Al toxicity, was used for the experiment (Edwards et al., 2012). Broadcast lime treatments were applied in October of 2008 and 2009 in Altus and Waukomis, and incorporated to approximately 8 cm depth with an S-Tine field cultivator with a rolling basket harrow same day the wheat was sowed. In addition, the field was chisel plowed to approximately 40 cm depth at the Altus site. Pelletized lime and TSP treatments were applied yearly in furrow in conjunction with planting.

### *3.3. Field Methodology*

All plots were sown using conventional tillage methods with a Hege small-plot conventional-drill planter. Nitrogen fertilizer was supplied at a level to ensure nitrogen fertility was not a limiting factor for grain yield (initial soil $NO_3$-N and N fertilizer accounting approx. 200 kg N $ha^{-1}$). Sowing dates are presented in Table 1, and planting density was approximately 2.1 million seeds $ha^{-1}$, or 67 kg $ha^{-1}$. Weeds and insects were controlled using commercially-available pesticides as needed. Plots at Waukomis were treated with a foliar fungicide at approximately Feekes GS 10 (Large, 1954), after flag leaf was fully emerged. Plots were harvested with a Hege self-propelled small plot combine, and harvest dates are presented on Table 1.

### *3.4. Vegetative Development Evaluations*

Plant population density was measured within one week of emergence by stand count one linear meter by one row in four different points within each plot. A method similar to the one described by Purcell (2000) was used to measure canopy closure. In this method digital photographs are taken in different stages of development, with the camera lens pointing down and encompassing approximately 1$m^2$ of the front part of each individual plot. The camera is mounted

Table 1. Planting and harvest dates for hard red winter wheat at Altus for the 2008-09, 2009-10, and 2010-11 growing seasons, and at Waukomis for the 2009-10, 2010-11, and 2011-12 growing seasons.

| | Altus | | Waukomis | |
|---|---|---|---|---|
| Growing season | Planting | Harvest | Planting | Harvest |
| 2008-2009 | 23-Oct-08 | 8-Jun-09 | – | – |
| 2009-2010 | 20-Oct-09 | 4-Jun-10 | 27-Oct-09 | 11-Jun-10 |
| 2010-2011 | 15-Oct-10 | 1-Jun-11 | 1-Oct-10 | 7-Jun-11 |
| 2011-2012 | – | – | 27-Sep-11 | 24-May-12 |

on a monopod attached to a piece of polyvinyl chloride (PVC) pipe. The mount remains 1m above the soil surface and the camera is inclined to avoid the PVC pipe from being included in the picture. Digital photographs were analyzed using a macro program for Sigma Scan Pro (v. 5.0, systat software, Point Richmond, CA) (Karcher and Richardson, 2005). The software has selectable options defining hue and saturation values. According to Purcell (2000), setting hue and saturation values selectively include the green pixels in the digital image. For this study hue was set for the range of 30 to 150, and saturation was set for the range of 0 to115. The output of the program is fractional canopy coverage, defined as the number pixels within the selected range divided by the total number of pixels per image (Purcell, 2000). Normalized-difference vegetative index (NDVI) measurements were taken using GreenSeekerTM sensor (model 505, NTech Industries, Ukiah, CA) at the same time as digital pictures. The by-plot coefficient of variation (CV) obtained from the NDVI readings were also analyzed, as it can be used as an indicator of plant population and homogeneity (Arnall et al., 2006). Fractional canopy cover assessment and NDVI readings were performed at regular intervals from emergence until the beginning of stem elongation.

Maximum solar light interception in each plot was quantified using a LI-COR Light Quantum Sensor (model LI 191, LI-COR Biosciences Inc., Lincoln, NE) at wheat heading in May 2011 and 2012 in the Waukomis site. At this same developmental stage, the number of heads per meter was counted on each plot to assess the effect of the different treatments on wheat heading. One linear meter was clipped from each plot to estimate harvest index, number of seeds per head, and seed weight prior to harvest.

### *3.5. Soil pH Assessment*

A composite soil sample of the trial area was taken before the establishment of the trial at both sites. To assess treatment effects on soil pH, composite samples were collected in October 2010 from each individual plot at Altus and Waukomis, and June 2011 and 2012 at Waukomis. The composite soil sample consisted of approximately 15 simple soil cores 0 – 15 cm depth. A total of 26 and 85 composite soil samples were collected from Altus and Waukomis over the 3 year period. Samples were oven-dried at 65°C for 24 h and ground to fit a 2-mm sieve (SERA-IEG-6, 2001).

A routine soil analysis was made to assess soil $NO_3$-N, P, and K, but the results were not used to determine crop fertilization needs, as N was fully supplied and P was a treatment. A combination pH electrode was used to measure soil pH in a 1:1 soil/water solution (Thomas, 1996). The analysis of extractable cations such as Ca, Mg, and K, was done using the Mehlich-3 procedure on the samples collected from Waukomis. Levels of extractable Al were determined using the Bertsch and Bloom (1996) method, by dissolving 5g of soil into 25 ml of 1M KCl. Aluminum, K, Mg, and Ca in the extracts were analyzed by inductively coupled plasma-atomic emission spectroscopy. The equation suggested by Sumner and Miller (1996) was used to determine the soil's effective cation exchange capacity (ECEC) as affected by the treatments:

$$ECEC \quad (meq/100g) = [K] + [Ca] + [Mg] + [Al_{KCl}] \qquad [1]$$

With the exception that Sumner and Miller (1996) suggests using Na as part of the equation, cation which was not assessed in this experiment. The Al saturation ($Al_{sat}$) was calculated as:

$$\% \quad Al_{sat} = (Al_{KCl} / ECEC) \quad X \quad 100 \qquad [2]$$

To assess the spatial extent of the change in pH caused by broadcast lime and in-furrow pelletized lime treatments in the soil profile, several pH point measurements were taken in the soil profile with a Spear Tip pH meter (model WD-35634-40, Pulse Instruments, Van Nuys, CA) in trenches opened after wheat harvest. Before opening the trench, a small portion of the soil (approximately 30 x 20 cm) was slowly saturated with approximately 12 liters of water using a drip plastic container placed above the plot. Twelve liters of water over a 30 x 20 cm area was enough to saturate the profile down to an approximate 20-cm depth. Therefore a trench 30 cm wide and 20 cm deep was opened in the saturated portion of the plots perpendicular to the wheat rows. Before introducing the probe into the soil, the respective point of the profile was watered with de-ionized water to create a localized wet paste that facilitated tip penetration and ensured pH reading at similar water contents. A plexiglas template (Figure 1) was used to ensure the points were measured at consistant distances from the pelletized lime band. The central hole of the template was placed on the banded lime furrow. Additional measurements were taken to each side horizontally at the following distances from the central point: 1.27cm, 2.54cm, 5.08cm, 7.62cm, and 10.16cm. Soil pH was measured below the application band in three directions, vertically and left and right diagonals, at the same distances measured horizontally. The pH was measured at 1.27cm and 2.54cm in the upper side of the profile (above lime band). After the readings were taken, the original soil was placed back the trench. This procedure was conducted for the control, 225 and 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime, and 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime at the Waukomis site in June 2011 and 2012.

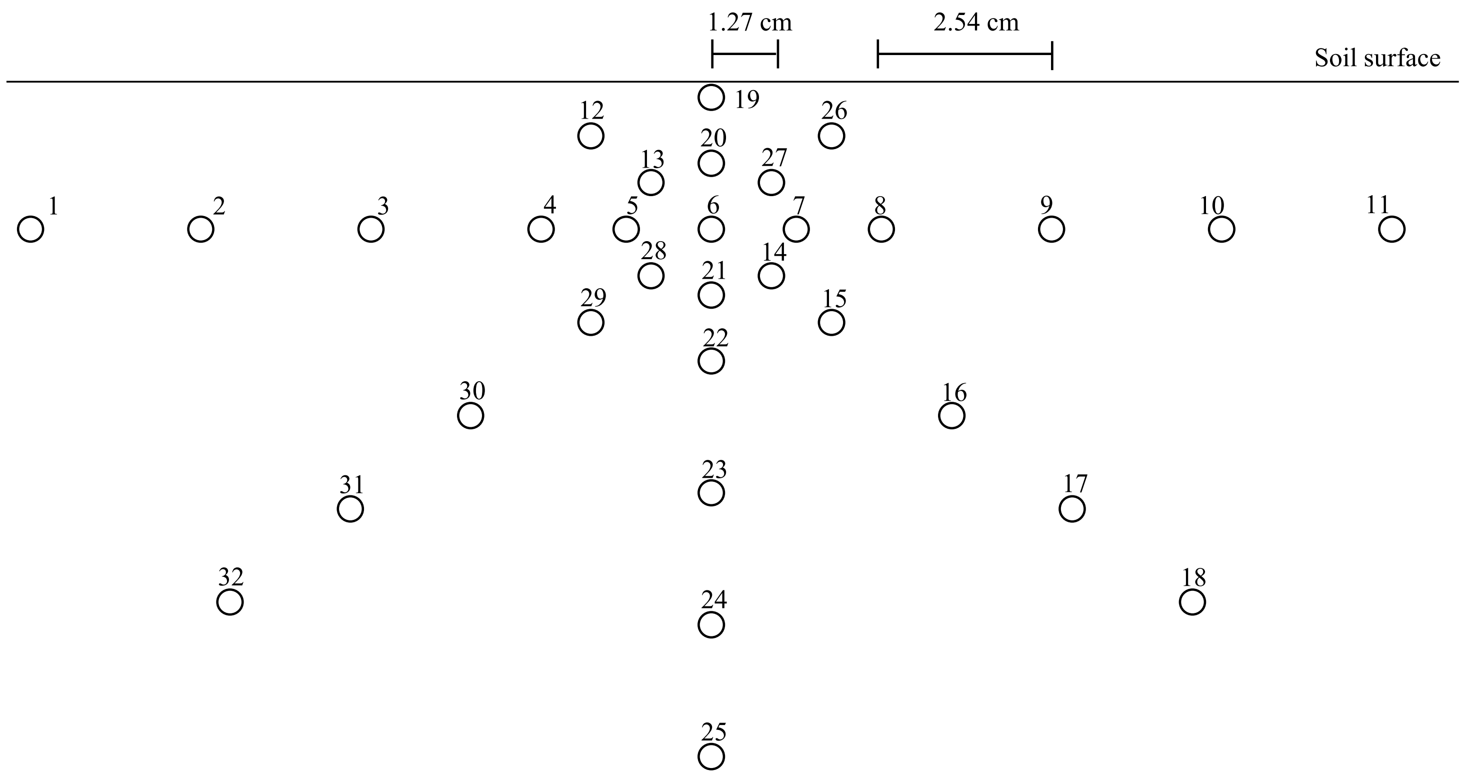


Figure 1. Representation of the plexiglas template used to ensure consistent point distribution of the pH measurements within the soil profile.

### *3.6. Economic Analysis*

Enterprise budgets were constructed to determine expected returns above variable costs for each of the seven acidity amendment strategies for Waukomis, using a method similar to Kaitibie et al. (2002). A different budget was constructed for each acidity amendment treatment for each year and was used to determine net returns above variable costs. Net returns were determined based on grain yield resulting from each treatment each year, and wheat grain prices were based on Oklahoma City cash price averaged over the months of June and July (Oklahoma Agric. Stat. Serv.). Wheat grain prices were US$0.15 kg$^{-1}$ in 2010, US$0.27 kg$^{-1}$ in 2011, and US$0.23 kg$^{-1}$ in 2012.

In this analysis the fixed costs were assumed to be constant for every treatment, and the variable costs were incorporated into the profit function to give a net return function. Variable costs included production practices such as seed, top-dress fertilizer, herbicide, insecticide and fungicide, and were considered to be equal for all the treatments, whereas the different liming, pelletized lime, and banded P fertilizer product and application costs changed according to treatment.

Prices for operating inputs such as seed, pesticides, diesel, and fertilizer, were collected from NASS (2012b) and indexes were used to adjust prices to the month when farmers were more likely to acquire each individual input. Lime costs were estimated based on local market price, and costs of delivery and application were included assuming an approximate 150 kilometer delivery. Broadcast agricultural price costs were estimated at US$0.04 kg$^{-1}$ (spread and incorporated), and pelletized lime price varied per year, but the average price was US$0.18 kg$^{-1}$ (applied in seed furrow). Prices for TSP were based on NASS (2012b) and averaged US$0.69 kg$^{-1}$ (banded with the seed). It was assumed that there was no difference in application costs between the two different rates of TSP or banded pelletized lime, because the drill with its fertilizer attachment would cover the same time and distance per unit area (Kaitibie et al., 2002). Harvest costs were US\$44.48 $ha^{-1}$ and US\$0.01 $kg^{-1}$ for each kilogram above 1345 kg $ha^{-1}$, representing actual regional costs of custom operations.

Broadcast lime costs were assessed as if they needed to be fully recovered at the year of application, or if they could be amortized over a 5-year period, accounting for the carry-over effect of lime (Lukin and Epplin, 2003). In this case the interest rates were based on the Federal Reserve Bank of Kansas City for the years in question (http://www.kansascityfed.org/research/indicatorsdata/agcredit/).

### *3.7. Statistical Analysis*

Data were analyzed using SAS Version 9.2 (SAS Institute, Cary, NC, 2001). Year was treated as a fixed effect as climatic patterns varied considerably from year to year. Year-specific soil pH and soil minerals, and wheat production factors such as crop stand, insolation at heading, harvest index, yield, and net economic return, were differentiated using ANOVA procedures with PROC GLM and a DUNCAN option to separate means in the MEANS statement at $\alpha = 0.05$. The 32 point pH measurements taken in the soil profile of each plot were analyzed within treatment using the ANOVA procedure described above, and the comparison for each point pH between an individual treatment and the same point in the control was performed using a TEST statement in PROC GLM, with a PDIFF option in an LSMEANS statement to separate the means. Regression analyses were performed using SigmaPlot 9 (Systat Software, 2004). Linear regression was used to determine the relationship of wheat grain yield to $Al_{sat}$, and non-linear regression was used in the analysis of Al behavior as function of soil pH.

CHAPTER IV

RESULTS AND DISCUSSION

### *4.1. Waukomis*

#### *4.1.1. Soil*

##### *4.1.1.1. Bulk Soil pH and Aluminum*

Bulk soil pH ranged from 4.90 to 5.93 and extractable Al ($Al_{KCl}$) from 0.38 to 20.18 mg $kg^{-1}$ in October 2010, and differences among treatments were significant for the two variables (Table 2). Pelletized lime at 450 kg $ha^{-1}$ $yr^{-1}$ slightly increased soil pH from the control (pH 5.08 compared to 4.90), and 2.25 and 4.50 Mg $ha^{-1}$ broadcast incorporated lime increased soil pH to 5.60 and 5.93. Extractable $Al_{KCl}$ was decreased significantly by the broadcast lime treatments from 20.1 mg $kg^{-1}$ to near-zero values, whereas 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime decreased $Al_{KCl}$ to 9.9 mg $kg^{-1}$, which was significantly different from the control. Neither 225 kg $ha^{-1}$ $yr^{-1}$ pelletized lime nor 28 or 56 kg $ha^{-1}$ $yr^{-1}$ TSP had a significant effect on soil pH or $Al_{KCl}$.

Soil pH values from June 2011 were significantly lower than those obtained in June 2010 (mean 4.98 versus 5.21). Values of soil pH ranged from 4.80 and 4.90 in the control and pelletized lime treatments to 5.45 in the 4.50 Mg ECCE $ha^{-1}$ incorporated lime. Lower soil pH resulted in higher $Al_{KCl}$ than June 2010 (mean 19.0 versus 11.1 mg $kg^{-1}$), but similar trends by treatment were observed. Pelletized lime at 450 kg $ha^{-1}$ $yr^{-1}$ resulted in significantly less $Al_{KCl}$

Table 2. Soil pH, exchangeable aluminum, exchangeable base cations, and effective cation exchange capacity as affected by soil acidity amendment strategy measured after three consecutive wheat growing seasons in a Grant Silt Loam at Waukomis, OK.

| Treatment | 2009 - 2010 | | | | | | 2010 - 2011 | | | | | | 2011 - 2012 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | pH | Al | Ca | Mg | K | ECEC† | pH | Al | Ca | Mg | K | ECEC | pH | Al | Ca | Mg | K | ECEC |
| | | mg kg$^{-1}$ | cmol$_c$ kg$^{-1}$ | | | | | mg kg$^{-1}$ | cmol$_c$ kg$^{-1}$ | | | | | mg kg$^{-1}$ | cmol$_c$ kg$^{-1}$ | | | |
| Control | 4.90d‡ | 20.1a | 4.38b | 2.26b | 0.55 | 7.41b | 4.80c | 30.2a | 4.61c | 2.38 | 0.48 | 7.79bc | 4.73c | 54.7ab | 4.39b | 2.23 | 0.54ab | 7.76c |
| 225 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 5.00cd | 12.3ab | 4.45b | 2.19b | 0.53 | 7.32b | 4.88c | 22.9ab | 4.58c | 2.32 | 0.47 | 7.61c | 4.75c | 51.8abc | 4.50b | 2.23 | 0.49c | 7.79c |
| 450 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 5.08c | 9.9b | 4.63b | 2.23b | 0.59 | 7.56b | 4.90c | 14.7bc | 5.30abc | 2.45 | 0.50 | 8.40abc | 4.85c | 39.3cd | 4.80b | 2.34 | 0.52b | 8.09abc |
| 28 kg ha$^{-1}$ yr$^{-1}$ TSP§ | 4.93cd | 19.1a | 4.37b | 2.27b | 0.54 | 7.39b | 4.85c | 27.1a | 4.80bc | 2.35 | 0.51 | 7.95bc | 4.73c | 60.7a | 4.45b | 2.32 | 0.53ab | 7.97bc |
| 56 kg ha$^{-1}$ yr$^{-1}$ TSP | 5.00cd | 14.9ab | 4.55b | 2.40ab | 0.57 | 7.68b | 4.88c | 26.6a | 4.69c | 2.40 | 0.49 | 7.88bc | 4.78c | 44.6bc | 4.65b | 2.38 | 0.54ab | 8.05abc |
| 2.25 Mg ha$^{-1}$ ECCE¶ | 5.60b | 0.6c | 5.80a | 2.66a | 0.57 | 9.04a | 5.30b | 8.4cd | 5.48ab | 2.58 | 0.50 | 8.64ab | 5.05b | 25.1de | 5.47a | 2.59 | 0.55a | 8.88ab |
| 4.50 Mg ha$^{-1}$ ECCE | 5.93a | 0.4c | 6.32a | 2.68a | 0.52 | 9.52a | 5.45a | 3.1d | 5.91a | 2.61 | 0.46 | 9.43a | 5.30a | 10.8e | 5.83a | 2.51 | 0.52b | 8.97a |
| Significance | | | | | | | | | | | | | | | | | | |
| Rep | NS | NS | ** | ** | *** | ** | NS | NS | * | *** | ** | ** | NS | * | * | ** | *** | ** |
| Treatment | *** | *** | *** | * | NS | *** | *** | *** | ** | NS | NS | * | *** | *** | *** | NS | ** | * |
| Residual | | | | | | | | | | | | | | | | | | |
| CV (%) | 1.87 | 49.44 | 8.69 | 8.98 | 5.82 | 7.49 | 1.57 | 30.2 | 9.07 | 5.92 | 4.96 | 6.92 | 2.09 | 23.39 | 8.84 | 9.62 | 3.31 | 7.36 |

*, **,***, NS Significant at $P = 0.05$, 0.01, 0.001, and non-significant
† ECEC, effective cation exchange capacity, calculated according to equation [1]
‡ Identical letters in the same column indicate no significant difference at $\alpha = 0.05$
§ TSP, triple super phosphate
¶ ECCE, effective calcium carbonate equivalent

than the control or TSP treatments, but not as low as 4.50 Mg ECCE $ha^{-1}$ agricultural lime. Soil samples collected in June 2012 confirmed the trend of decreasing soil pH (mean 4.87) and increasing extractable Al (median 40.9 mg $kg^{-1}$) when compared to previous years of the study. The significant advantage of broadcast incorporated ag-lime over the other treatments persisted in 2012, with higher soil pH and lower $Al_{KCl}$ levels.

Slight changes in soil pH caused by yearly application of small quantities of pelletized lime are documented on the literature (Godsey et al., 2007; Higgins et al., 2012). Higgins et al. (2010), for example, showed that 0.18, 0.35, and 0.53 Mg $ha^{-1}$ $yr^{-1}$ of lime resulted in a mean increase in soil pH of 0.07, 0.09, and 0.25 units approximately 21 months after application. Results from the present study showed similar effects on soil pH by pelletized lime, as 225 and 450 kg $ha^{-1}$ $yr^{-1}$ of pelletized lime increased soil pH 0.10 and 0.18 units (Table A3, Appendix). However, the magnitude of pH change and Al reduction is a function of the amount of lime applied (Godsey et al., 2007; Pierce and Warncke, 2000; Scott et al., 1997; Scott and Coombes, 2006; Tang et al., 2003), thus 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime resulted in greater change in both parameters than pelletized lime.

The robust increase in soil $Al_{KCl}$ between years is explained by the exponential relationship of $Al_{KCl}$ as a function of soil pH (Figure 2A). For instance a decrease in 0.48 units in soil pH from 5.93 to 5.45, as occurred between October 2010 and June 2011 in the 4.50 Mg ECCE $ha^{-1}$ agricultural lime, caused a relatively small increase in $Al_{KCl}$ from 0.4 to 3.1 mg $kg^{-1}$ (Table 2). However, a decrease of only 0.07 units, from 4.80 to 4.73, as the one occurred in the control plots between June 2011 and June 2012, caused a large increase in $Al_{KCl}$, shifting it from 30.2 to 54.7 mg $kg^{-1}$ (Table 2). The behavior of $Al_{sat}$ was similar to $Al_{KCl}$, as a significant inverse exponential relationship was also found between $Al_{sat}$ and pH (Figure 2B), and therefore shifts in $Al_{sat}$ were more prominent at low pH levels. Percent $Al_{sat}$ found in the Grant Silt Loam in this study rarely surpassed 9%, with relatively low $Al_{sat}$ when compared to other acid soil studies conducted in Oklahoma (Johnson et al., 1997; Kariuki et al., 2007; Wise, 2002). For example, decreasing soil pH in the control plots from 4.90 to 4.73 in the present study increased $Al_{sat}$ levels from 3.3 to 7.82%. In a similar study conducted in Perkins, OK, $Al_{sat}$ reached up to 55% at pH of 4.7 (Kariuki et al., 2007).

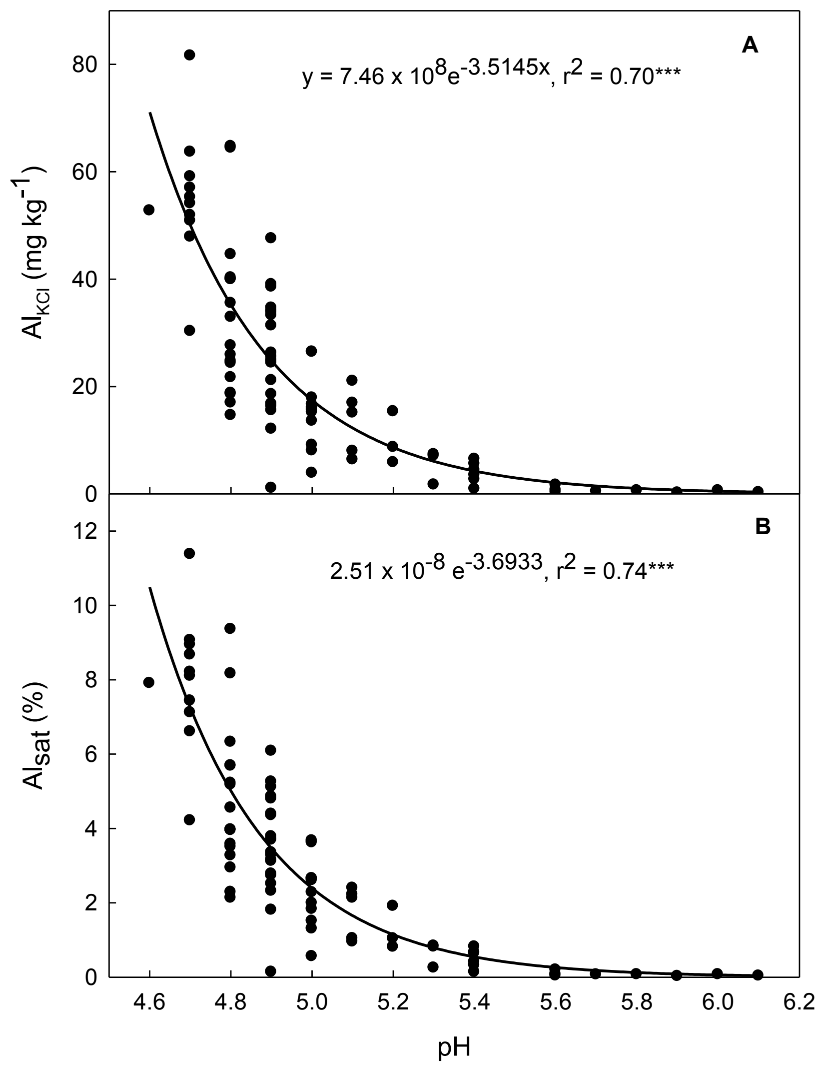


Figure 2. Inverse exponential relationship between (A) aluminum concentration ($Al_{KCl}$, 1.0 *M* KCl extraction, mg $kg^{-1}$) and (B) Al saturation ($Al_{sat}$, %) and soil pH for a Grant Silt Loam soil at Waukomis, OK. *** Significant at $P < 0.001$.

### *4.1.1.2. pH Changes Across the Soil Profile*

Differences in pH values across the soil profile were significant within treatment for all treatments, both years (Figure 3). In June 2011, pelletized lime at 225 and 450 kg $ha^{-1}$ $yr^{-1}$ raised soil pH to values > 5.0 only at and around the pellet (Figures 3B and 3C). In fact, point pH measurements in 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime ranged between 5.27 and 5.97 at and around the pellet, and were as low as 4.07 deeper in the profile in June 2011. Conversely, broadcast agricultural lime at 2.25 and 4.50 Mg $ha^{-1}$ induced greater soil pH amelioration throughout the profile (i.e., 27 out of 32 points with pH > 5 at 4.50 Mg ECCE $ha^{-1}$ agricultural lime, Figure 3E). Lower application rates of agricultural lime and pelletized lime produced similar results as their respective higher rate treatments in June 2011. A general trend higher pH in points closer to soil surface than points deeper in the profile was observed in the control treatment (Figures 3A and 3F). Liu et al. (2004) also found similar results when comparing soil pH measurements from 2 cm and 2 to 5 cm depth.

Soil pH from 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime and 4.50 Mg ECCE $ha^{-1}$ agricultural lime treatments followed analogous patterns in June 2012 to those observed in June 2011 (Figures 3H and 3J). The 225 kg $ha^{-1}$ $yr^{-1}$ pelletized lime and 2.25 Mg ECCE $ha^{-1}$ agricultural lime treatments had less evident effects on soil pH than in 2011 (Figures 3G and 3I). Rainfall in the period between the pellet introduction into the soil and pH readings was greater in 2011-2012 than in 2010-2011 (592 versus 421 mm), thus greater amount of precipitation and yearly cultivation of the soil probably increased the dissolution and leaching of lime, resulting in less evident effects of low rates of both liming treatments on soil pH.

Changes in soil pH induced by pelletized lime were significantly different from the control only in the immediate vicinity of the pellet placement (Figures 4A, 4B, and 4F), and pelletized lime at 225 kg $ha^{-1}$ $yr^{-1}$ was no different than the nontreated control in 2012 (Figure

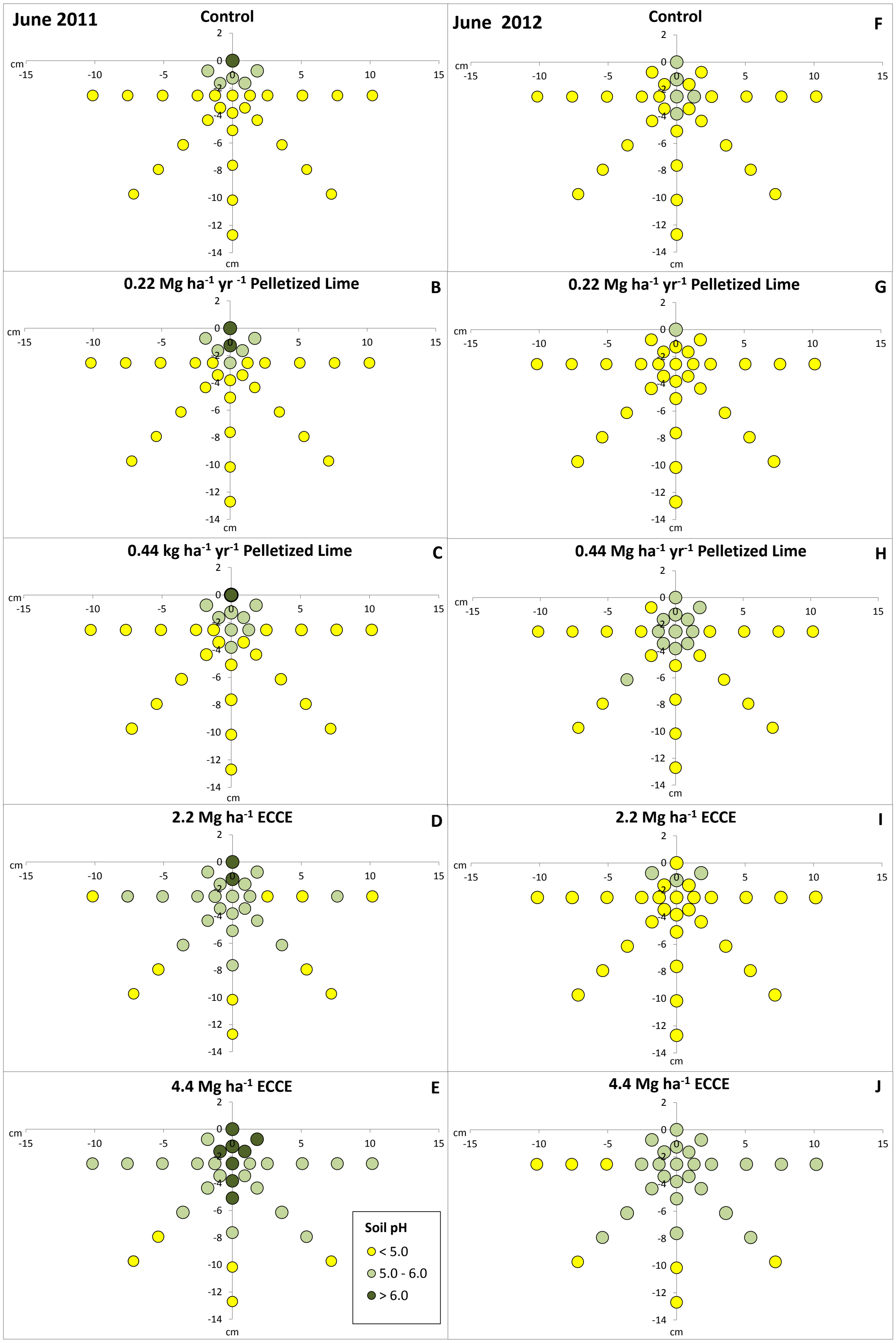


Figure 3. Distribution of pH across the soil profile as a function of acidity correction strategy measured in June 2011 and June 2012 for a Grant Silt Loam at Waukomis, OK.

4E). The 450 kg ha$^{-1}$ yr$^{-1}$ pelletized lime treatment presented more points with pH significantly different from the control in June 2012 than 2011, possibly accounting for a cumulative effect of yearly application. With exception of 2.25 Mg ECCE ha$^{-1}$ agricultural lime in June 2012 (Figure 4G), broadcast incorporated agricultural lime presented a broader change in soil pH than did pelletized lime, with values significantly different from the nontreated control throughout the incorporation depth (Figures 4C, 4D, and 4H).

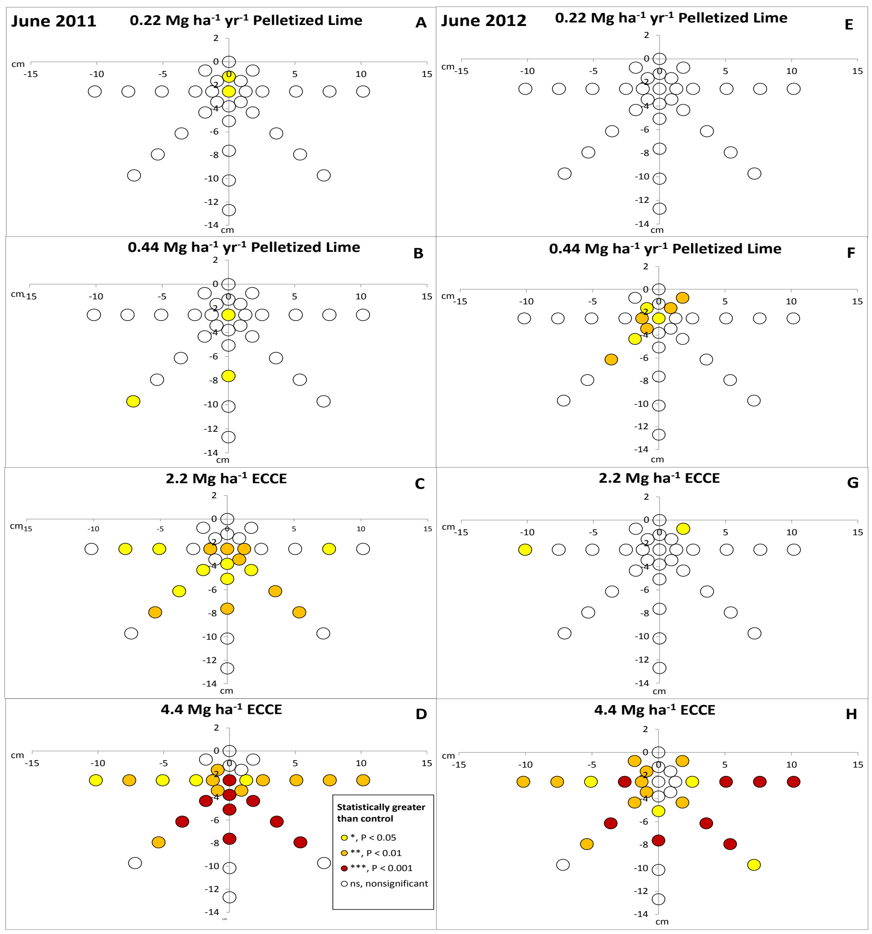


Figure 4. Significance of the difference between point soil pH with acidity amendment strategy and the same point in the nontreated control treatment measured in June 2011 and June 2012 in a Grant Silt Loam soil at Waukomis, OK. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, ns, non-significant.

The peaks in soil pH at and around the pellet caused by in furrow pelletized lime may be function of slower reaction time for pelletized lime when compared to ground lime (Pierce and Warncke, 2000). The lack of diffusion of pelletized lime was evident when opening the trenches in the soil profile, as the pellets of lime could be observed in the same point where they were applied approximately 220 days before (Figure 5). Pierce and Warncke (2000) attributed the slow reaction of pelletized lime to the presence of the lignosulfate binding agent, which delayed the breakdown of the pellets. The results in this study validate the suggestion that pelletized lime performs like large lime particles (Pierce and Warncke, 2000), with very low dissolution and reaction rates (Álvarez et al., 2009).

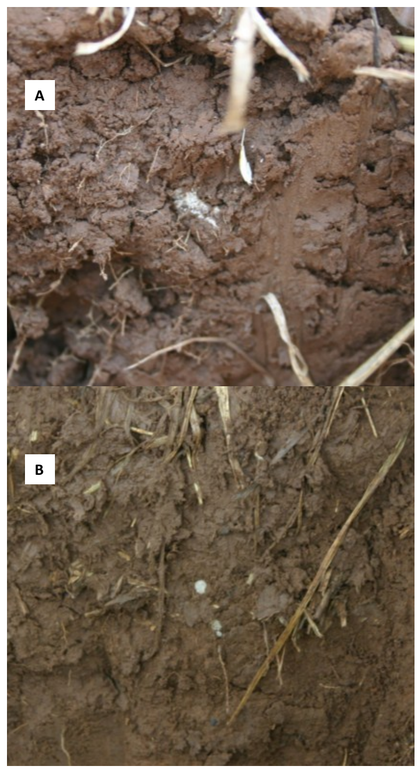


Figure 5. Trench opened in June 2011 (A) and June 2012 (B) depicting the lack of diffusion of the pelletized lime throughout the soil profile, with pellets still visible and unmodified after approximately 220 days from pelletized lime application.

#### *4.1.1.3. Exchangeable Cations and Mehlich-3 Extractable Phosphorus*

Extractable Ca was consistently greater in 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime treatments and in 450 kg $ha^{-1}$ $yr^{-1}$ pelletized in June 2011 (Table 2). These same treatments also resulted in greater ECEC than most other treatments in this study. Magnesium was higher for 2.25 and 4.50 Mg $ha^{-1}$ broadcast lime in October 2010, and, although Mg levels were still higher in June 2011 and June 2012, differences from the control or remaining treatments were not significant. The ground lime applied was composed of 30% Ca and 3.7% Mg, which would account for 0.14 and 0.28 Mg $ha^{-1}$ of Mg in the 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime treatments, explaining the higher levels of Mg found in the samples from these treatments. The pelletized lime, although composed of 10.3% Mg, had no substantial effect on bulk soil Mg levels. Potassium was not affected by treatment in October 2010 or June 2011 and, although there was a significant difference among treatments in June 2012, the range of soil K measured in this study was very narrow (0.49 – 0.55 $cmol_c$ $kg^{-1}$). These findings are in agreement with prior research indicating higher Ca, Mg and ECEC as a function of lime application, and K not affected by liming, reported for a wide range of soils and climate characteristics (Blevins et al., 1978; Caires et al., 2002; Caires et al., 2005; Caires et al., 2006; Haling et al., 2010; Higgins et al., 2012; Pavan et al., 1984; Scott and Coombes, 2006).

Initial levels of Mehlich-3 extractable P were 23.5 mg $kg^{-1}$ in October 2009 when the experiment was established (Figure 6). There was no significant difference in extractable P among treatments in October 2010; however, P levels ranged from 19.6 to 23 mg $kg^{-1}$ in June 2011, and significantly lower P levels resulted from 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime, 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime. Differences were greater in June 2012, when soil P was 21.3 and 20.1 mg $kg^{-1}$ in 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime; 23.4 mg $kg^{-1}$ in both 225 and 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime; and 25.5 and 26.2 mg $kg^{-1}$ in TSP at 28 and 56 kg $ha^{-1}$. Decrease in extractable P due to liming acid soils has been previously reported (Anjos and Rowell, 1987;

Haynes, 1982; Murrmann and Peech, 1969), and occurs due to higher phosphate adsorption after liming (Curtin and Syers, 2001). Additionally, Westermann (1992) suggested that P availability is affected by the surface area of lime in calcareous soils and, therefore, P fertilization should be increased when lime is applied. Alternatively, the increase in soil extractable P due to continuous phosphate fertilizer application has also been reported by previous researches and the findings for 28 and 56 kg $ha^{-1}$ $yr^{-1}$ TSP in this study are in consistent with literature (Conte et al., 2003, McCollum, 1991; Murrmann and Peeche, 1969; Zhang et al., 2004).

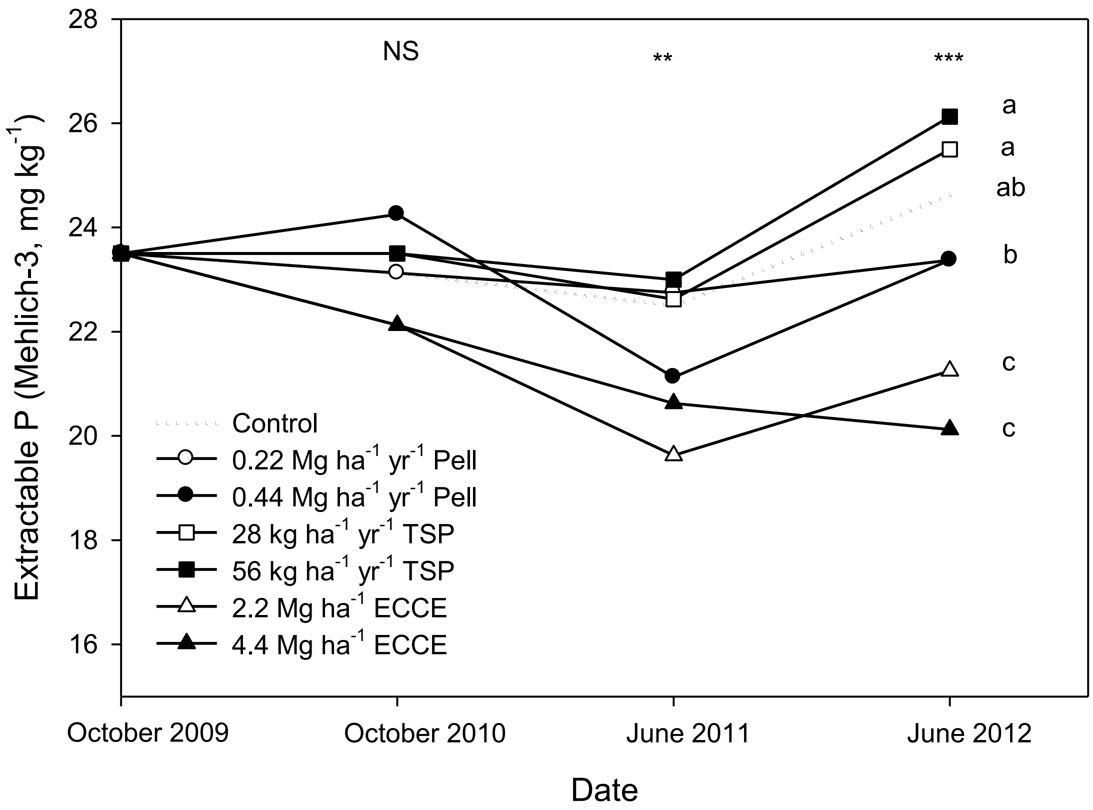


Figure 6. Soil Mehlich-3 extractable phosphorus in time as affected by soil acidity amendment strategies for a Grant Silt Loam soil at Waukomis, OK. Pell, pelletized lime; TSP, triple superphosphate; ECCE, effective calcium carbonate equivalent broadcast and incorporated; differences among treatments significant at ** $P < 0.01$; *** $P < 0.001$; NS, non-significant.

### *4.1.2. Wheat Crop*

#### *4.1.2.1. Weather*

Monthly rainfall and reference evapotranspiration ($ET_0$), estimated by the FAO (Food and Agricultural Organization of the United Nations, Rome, Italy) modified form of the Penman-Monteith equation, as well as 30-yr normal precipitation for Waukomis, OK, are presented in Table 3 for the three years of the study. The 2009-2010 growing season was characterized by favorable conditions at planting, dry fall, and close-to-normal-precipitation spring; the 2010-2011 growing season had good planting conditions but severe drought throughout the remaining of the season; and the 2011-2012 growing season had dry initial conditions but a plenitude of water from late October until the end of the season.

Table 3. Monthly reference evapotranspiration and total precipitation for the 2009-2010, 2010-2011, and 2011-2012 winter wheat growing seasons at Waukomis, OK.

| | 2009-2010 | | 2010-2011 | | 2011-2012 | | |
|---|---|---|---|---|---|---|---|
| Month | $ET_0$† | Rainfall | $ET_0$ | Rainfall | $ET_0$ | Rainfall | 30-yr Normal‡ |
| | mm | | | | | | |
| October | 69 | 150 | 108 | 71 | 114 | 84 | 78 |
| November | 60 | 10 | 66 | 56 | 60 | 96 | 57 |
| December | 37 | 8 | 40 | 0 | 32 | 73 | 35 |
| January | 36 | 31 | 42 | 5 | 61 | 24 | 27 |
| February | 32 | 29 | 57 | 15 | 54 | 61 | 38 |
| March | 73 | 45 | 89 | 45 | 99 | 62 | 68 |
| April | 119 | 68 | 158 | 41 | 119 | 169 | 79 |
| May | 144 | 197 | 171 | 186 | 185 | 15 | 121 |
| GS§ Total | 571 | 538 | 730 | 421 | 724 | 585 | 503 |

† Reference evapotranspiration estimated by the Penman-Monteith methodology modified by FAO (Food and Agriculture Organization, Rome, Italy)
‡ 30 year normal precipitation
§ Winter wheat growing season at Waukomis, OK (October – May)

#### *4.1.2.2. Crop Development*

##### *4.1.2.2.1. Canopy Cover and Insolation*

Treatment affected canopy closure all three growing seasons (Table 4). Banded TSP resulted in greater winter wheat canopy cover in December, prior to winter dormancy, in every year of the study regardless of weather conditions (Table 4). Phosphate fertilizer also generated greater spring canopy cover in the 2009-2010 and 2010-2011 growing seasons. Broadcast agricultural lime resulted in fall and spring canopy cover comparable to banded TSP and thus greater than control or pelletized lime in 2010-2011 when low soil pH effects were exacerbated in the non-limed plots due to a severe drought. Responses in canopy cover associated with pelletized lime were not significantly different from the control in any rate applied or growing season studied. Banded TSP or broadcast agricultural lime led to greater insolation at heading in 2010-2011; however, there were no significant differences among treatments on insolation at heading in 2011-2012, when more abundant and distributed moisture ensured maximum final canopy cover achievement by all the treatments (Table 4).

Canopy cover prior to winter dormancy in December 2009 was significantly different among treatments, with the nontreated control and pelletized or ground lime treatments averaging 7%, and 28 and 56 kg ha$^{-1}$ yr$^{-1}$ TSP reaching 13 and 18% canopy coverage (Table 4). Rainfall and temperature during November and December are critical for crop establishment and fall tillering of winter wheat in the Great Plains (McMaster and Wilhelm, 2010). Scarce precipitation (18 mm cummulative in November and December) and low average temperatures (430° thermal units and 97 mm of $ET_0$ accumulated from planting to December) led to low canopy cover values in December 2009. Canopy cover reached in April 2010, when approximately 1025° Tu were accumulated, was significantly different among treatments and ranged from 65% in the control to 91% in the 56 kg ha$^{-1}$ yr$^{-1}$ TSP.

Table 4. Effects of soil acidity amendment strategy on canopy coverage obtained via digital imagery prior to winter dormancy (Fall), post winter dormancy prior to flowering (Early spring), and percent insolation at heading obtained via LI-COR Light Quantum Sensor in the 2009-2010, 2010-2011, and 2011-2012 growing seasons at Waukomis, OK.

| | 2009-2010 | | 2010-2011 | | | 2011-2012 | | |
|---|---|---|---|---|---|---|---|---|
| Treatment | Fall† | Early spring‡ | Fall | Early spring | Insolation§ | Fall | Early spring | Insolation |
| | % | | | | | | | |
| Control | 7c¶ | 65c | 59b | 76b | 49b | 75b | 95 | 89 |
| 225 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 7c | 66c | 54b | 70b | 48b | 68b | 95 | 87 |
| 450 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 7c | 70c | 54b | 72b | 60ab | 73b | 94 | 86 |
| 28 kg ha$^{-1}$ yr$^{-1}$ TSP†† | 13b | 83ab | 80a | 84ab | 60ab | 77ab | 94 | 90 |
| 56 kg ha$^{-1}$ yr$^{-1}$ TSP | 18a | 91a | 89a | 91a | 71a | 86a | 96 | 92 |
| 2.25 Mg ha$^{-1}$ ECCE‡‡ | 7c | 76bc | 83a | 91a | 74a | 68b | 93 | 90 |
| 4.50 Mg ha$^{-1}$ ECCE | 7c | 73bc | 78a | 83ab | 62ab | 73b | 94 | 88 |
| Significance | | | | | | | | |
| Rep | * | ** | NS | NS | NS | NS | NS | * |
| Treatment | *** | ** | *** | ** | * | * | NS | NS |
| Residual | | | | | | | | |
| CV (%) | 21.3 | 10.1 | 13.4 | 9.88 | 19.8 | 9.32 | 1.78 | 2.96 |

*, **,***, NS Significant at p = 0.05, 0.01, 0.001, and non-significant, respectively
† Canopy cover achieved in the fall, with 430, 868, and 902 thermal units (°C) accumulated for 2009-2010, 2010-2011, and 2011-2012, respectively
‡ Canopy cover achieved in the spring, with 1025, 1242, and 1372 thermal units (°C) accumulated for 2009-2010, 2010-2011, and 2011-2012, respectively
§ Percent insolation at heading
¶ Identical letters in the same column indicate no significant difference at α = 0.05
†† TSP, triple super phosphate applied with seed in furrow
‡‡ ECCE, effective calcium carbonate equivalent, broadcast and incorporated

Despite better conditions at planting in 2010-2011, the fall was particularly dry with 128 mm total precipitation. This precipitation, however, was well distributed, and combined to higher average temperatures (total fall of 868° Tu and 213 mm of $ET_0$), allowed 28 and 56 kg $ha^{-1}$ $yr^{-1}$ TSP and 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime to achieve near maximum canopy cover by December 2010 (Table 4). The control, 225 and 450 kg $ha^{-1}$ $yr^{-1}$ pelletized lime reached 59, 54, and 54% canopy cover in December 2010. In the 2011-2012 growing season, development of canopy cover was delayed until late October due to dry initial conditions, and maximum canopy cover was not reached prior to winter dormancy in any of the treatments (Table 4). Still, there was a significant difference in fall canopy cover among treatments and banded TSP at 56 kg $ha^{-1}$ $yr^{-1}$ reached 86% canopy closure while 225 kg $ha^{-1}$ $yr^{-1}$ pelletized lime reached 68%. Despite the significant differences in canopy cover among treatments prior to winter dormancy in the 2010-2011 and 2011-2012 seasons, canopy cover above 53% is sufficient for winter wheat to reach maximum relative yields in Oklahoma (Butchee, 2011), and therefore the differences observed in December 2010 and 2011 may not have been enough to induce grain yield differences on this study.

#### *4.1.2.2.2. Normalized Difference Vegetative Index*

As expected, normalized difference vegetative index (NDVI) response to treatment was similar to that of canopy closure throughout the growing seasons (Martin et al., 2007). Banded TSP at 56 kg $ha^{-1}$ $yr^{-1}$ resulted in the greatest NDVI values in every year of the study (Table 5). Similar results were obtained from broadcast agricultural lime in the 2010-2011 growing season, when severe drought made acidity effects more apparent. Significant differences among treatments were observed throughout the three growing seasons.

In December 2009 (Fall), NDVI ranged from 0.21 in the broadcast lime and control treatments to 0.26 in the 56 kg $ha^{-1}$ $yr^{-1}$ TSP, with most treatments performing similarly. By April

Table5. Effect of acidity amendment strategy on normalized difference vegetative index (NDVI) obtained via GreenSeeker sensor prior to winter dormancy (Fall) and post winter dormancy prior to flowering (Early spring) during the 2009-2010, 2010-2011, and 2011-2012 growing seasons at Waukomis, OK.

| | 2009-2010 | | 2010-2011 | | 2011-2012 | |
|---|---|---|---|---|---|---|
| Treatment | Fall† | Early spring‡ | Fall | Early spring | Fall | Early spring |
| Control | 0.22c§ | 0.59c | 0.46c | 0.64c | 0.64c | 0.82ab |
| 225 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 0.22c | 0.61bc | 0.46c | 0.63c | 0.62cd | 0.82ab |
| 450 kg ha$^{-1}$ yr$^{-1}$ Pell Lime | 0.22c | 0.61bc | 0.49c | 0.67cb | 0.61d | 0.79bc |
| 28 kg ha$^{-1}$ yr$^{-1}$ TSP¶ | 0.24b | 0.69ab | 0.65b | 0.72ab | 0.67b | 0.82ab |
| 56 kg ha$^{-1}$ yr$^{-1}$ TSP | 0.26a | 0.75a | 0.75a | 0.76a | 0.74a | 0.83a |
| 2.25 Mg ha$^{-1}$ ECCE†† | 0.21c | 0.60c | 0.65b | 0.74a | 0.62cd | 0.78c |
| 4.50 Mg ha$^{-1}$ ECCE | 0.21c | 0.60c | 0.66b | 0.73a | 0.62cd | 0.81ab |
| Significance | | | | | | |
| Rep | *** | ** | ** | * | * | * |
| Treatment | *** | ** | *** | *** | *** | * |
| Residual | | | | | | |
| CV (%) | 2.61 | 8.23 | 6.45 | 4.48 | 2.39 | 1.91 |

*, **,***, NS Significant at $P = 0.05$, 0.01, 0.001, and non-significant, respectively

† NDVI achieved in the fall, with 430, 868, and 902 thermal units (°C) accumulated for 2009-2010, 2010-2011, and 2011-2012

‡ NDVI achieved in the spring, with 1025, 1242, and 1372 thermal units (°C) accumulated for 2009-2010, 2010-2011, and 2011-2012

§ Identical letters in the same column indicate no significant difference at $\alpha = 0.05$

¶ TSP, triple super phosphate applied with seed in furrow

†† ECCE, effective calcium carbonate equivalent, broadcast and incorporated

2010 (Early spring), differences among treatments regarding NDVI persisted, with clear advantage to both rates of banded TSP over the other treatments. In the dry growing season of 2010-2011, 28 and 56 kg ha$^{-1}$ yr$^{-1}$ TSP and 2.25 and 4.50 Mg ha$^{-1}$ agricultural lime resulted in greater NDVI values. Pelletized lime and control presented lower NDVI values throughout the cycle, reflecting the lower values of canopy cover. In the 2011-2012 growing season, all the treatments reached good development and high NDVI due to higher average rainfall; however, TSP resulted in the highest NDVI values, analogous to canopy cover development. The strong relation between NDVI and canopy cover found in this experiment (Figure 7) is supported by previous research with winter wheat in Oklahoma (Butchee, 2011).

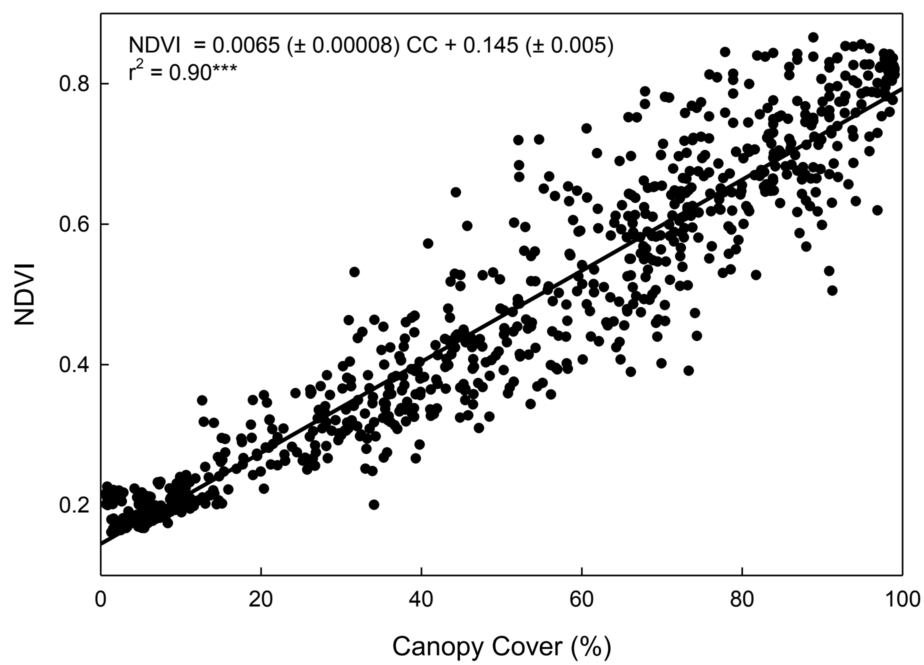


Figure 7. Relationship between canopy coverage obtained via digital photography and normalized vegetative difference index (NDVI) obtained via GreenSeeker sensor taken throughout the 2009-2010, 2010-2011, and 2011-2012 winter wheat growing seasons at Waukomis, OK. SE, standard error.

Greater vegetative development resulting from additional phosphate fertilization in wheat observed in the three years of this trial is supported by previous research (Phillips et al., 2000; Rodríguez et al., 1998; Sandaña and Pinochet, 2011; Sandaña et al., 2012). Phosphorus has direct effect on wheat tillering (Rodríguez et al., 1998; Rodríguez et al., 1999; Sato et al., 1996) and rate of individual leaf expansion (Rodríguez et al., 2000), and, therefore, wheat development can be delayed when no P fertilizer is added (Rodríguez et al., 1998; Rodríguez et al., 1999; Sandaña and Pinochet, 2011; Sandaña et al., 2012).

Broadcast incorporated agricultural lime effects on wheat growth and development changed by season. The rate and extent reaction of lime with the soil is influenced by soil moisture and it is slower when the soil is dry (Liu et al., 2004; Zhang and Raun, 2006); thus, changes in soil pH observed in the 2009-2010 growing season probably occurred mostly during the spring 2010 as lime was applied at planting in 27 October 2009, and was followed very dry November and December. Therefore, initial crop development in the 2009-2010 growing season was restricted by low soil pH and very dry conditions, explaining wheat growth in the limed plots similar to the control or the pelletized lime throughout the growing season. Low pH effects on the early development stages of wheat are irreversible, even when low soil pH is corrected later in the season (Liu et al., 2004).

Severe drought most likely influenced crop response to lime treatment in the 2010-2011 growing season, as the detrimental effects of low soil pH and Al are greater under dry conditions (Caires et al., 2006; Krizek et al., 1988; Krizek and Foy, 1988). The ability of wheat roots to uptake water is decreased when Al is present (Kauffman and Gardner, 1978); therefore, soil acidity effects on crops are exacerbated in dry years when compared to wet years. Krizek and Foy (1988) found that dry conditions combined with Al stress magnified the differences in vegetative growth of barley when compared to higher soil moisture levels. Greater wheat biomass due to increased soil pH has previously been reported (Kaitibie et al., 2002; Scott and Coombes, 2006;

Tang et al., 2003) and was stated to occur due to greater tillering (Mahler and McDole, 1987). This is in accordance to the higher canopy cover and NDVI values resultant from broadcast agricultural lime in the dry season of 2010-2011 when compared to the untreated control.

#### *4.1.2.2.3. Plant Population Homogeneity*

A good indicator of plant population uniformity is the CV derived from NDVI readings. Values above 17% indicate wheat population density below 100 plants $m^{-2}$ (Arnall et al., 2006). There was no significant effect of treatment on NDVI CV in 2009-2010 (Figure 8). Plant population uniformity, however, was significantly affected by treatment in both December 2010 and March 2011, with banded TSP consistently resulting in lower NDVI CV values (i.e. greater homogeneity) than the other treatments (Figure 8). Broadcast incorporated agricultural lime at 2.25 and 4.50 Mg ECCE $ha^{-1}$ also resulted in lower NDVI CV values in the dry 2010-2011 growing season. The untreated control and pelletized lime at 225 kg $ha^{-1}$ $yr^{-1}$ resulted in NDVI CV values higher than 17% and thus poorer population and greater heterogeneity. The 2011-2012 growing season was characterized by a moister fall, which led to greater uniformity across all the treatments, and NDVI CV did not reach critical values of 17%. Thus, the performance of the plots with higher soil pH, where lime was applied, was not as evident as the previous dryer season. Nevertheless, significant differences were found in NDVI CV between treatments in December 2011 and March 2012, with TSP resulting in better plant uniformity than the other treatments.

Banded TSP resulted in higher NDVI and lower NDVI CV throughout the three growing seasons. A detailed comparison between the TSP and the control, regarding the better vegetative development and plant uniformity as a result of banded TSP in the 2010-2011 and 2011-2012 growing seasons is provided in Figure 9. Greater plant homogeneity induced by P fertilization has been reported by Rodríguez et al. (1998) and Rodríguez et al. (1999), who indicated that the P-induced homogeneity of wheat crops is a function of the increased rate and decreased duration of

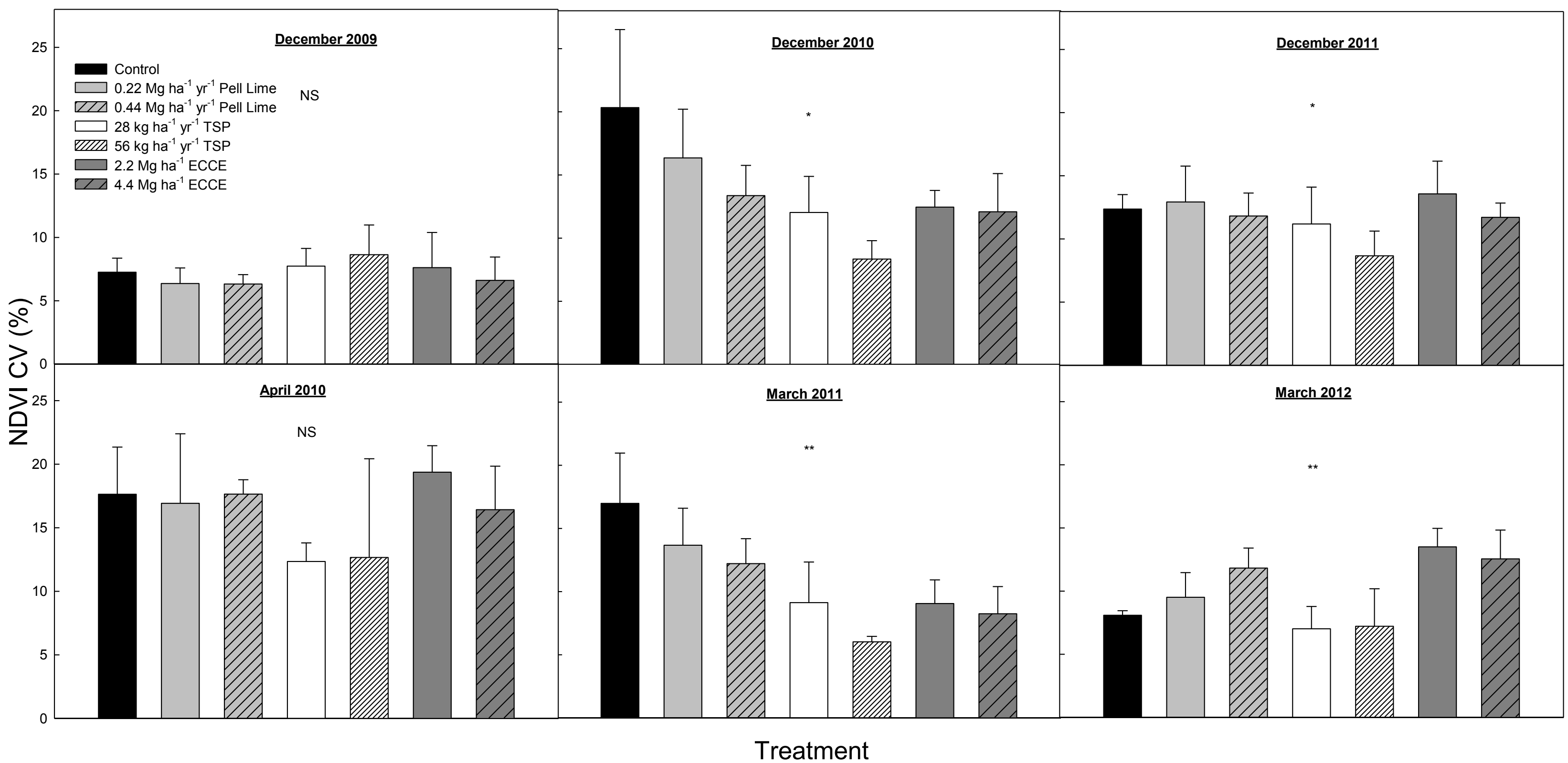


Figure 8. Mean normalized difference vegetative index coefficient of variation (NDVI CV) determined from each plot for each acidity amendment treatment prior to winter dormancy (December) and post winter dormancy prior to flowering (March or April), for winter wheat growing seasons 2009-2010, 2010-2011, and 2011-2012, at Waukomis, OK. *, ** Significant differences among treatments for that specific month at $P = 0.05$ and 0.01; NS, non-significant. Vertical error bars indicate standard deviation

tiller emergence. A more uniform plant population will decrease intra- and inter- specific competition in the crop (Rodríguez et al., 1999), enhance the utilization of resources such as N fertilizer, and achieve maximum yields (Arnall et al., 2006; Morris et al., 2006).

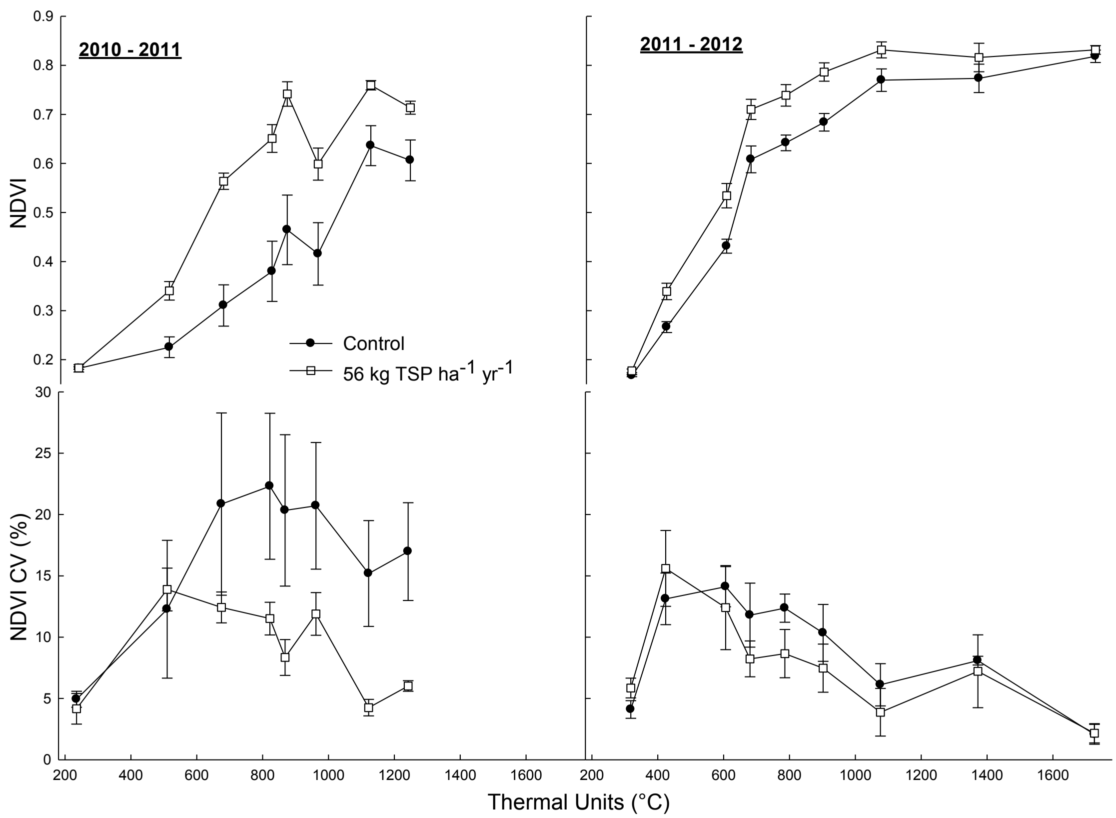


Figure 9. Mean normalized difference vegetative index (NDVI) and coefficient of variation from NDVI readings (NDVI CV) obtained via GreenSeeker sensor as a function of thermal units with and without phosphate fertilization in an acid Grant Silt Loam during winter wheat growth stages Feekes GS 1 to Feekes GS 5, for the 2010-2011 and 2011-2012 growing seasons at Waukomis, OK. Vertical error bars indicate standard deviation of the mean.

#### *4.1.2.3. Grain Yield*

##### *4.1.2.3.1. Wheat Yield Components*

Soil moisture conditions at sowing were more favorable for wheat planting and emergence in October 2010 than in October 2011 (83 mm versus 53 mm 30-day cumulative rainfall prior to planting), resulting in greater mean plant population density in 2010-2011 when compared to 2011-2012 (31 versus 22 plants $m^{-1}$). However, acidity amendment treatment had no significant effect on crop stand in either of the seasons. Pelletized lime at 225 kg $ha^{-1}$ $yr^{-1}$ resulted in significantly fewer heads per meter than the other treatments in 2010-2011, and harvest index, seed weight, and number of seeds per spike were not affected by treatment in the 2010-2011 growing season (Table 6).

In the growing season 2011-2012, where greater uniformity among treatments was observed, the only yield component where significant differences were observed among treatments was harvest index (HI). Lowest values of HI resulted from 28 and 56 kg $ha^{-1}$ $yr^{-1}$ banded TSP and by 225 kg $ha^{-1}$ $yr^{-1}$ pelletized lime. However, HI should be interpreted cautiously. It is a more conservative variable, not being positively affected by phosphate fertilization (Sandaña and Pinochet, 2011). Yet, wheat HI can be decreased by Al concentrations higher than 0.62 (± 0.12) $cmol_c$ $kg^{-1}$ in Al-sensitive cultivars (Valle et al., 2009). Therefore, soil $Al_{KCl}$ levels of 44 – 60 mg $kg^{-1}$ (or 0.50 – 0.67 $cmol_c$ $kg^{-1}$) observed in the TSP plots in 2011-2012, in addition to highest canopy cover and NDVI (indicators of greater biomass), may have led to lower HI values in the plots fertilized with TSP. The differences between the seasons 2010-2011 and 2011-2012 are clear, with greater values of heads per meter (mean 99 against 76 heads $m^{-1}$), harvest indexes (mean 0.35 against 0.21), seed weight (mean 2.87 against 2.33 g per 100 seeds), and number of seeds per spike (mean 27 against 12 seeds $spike^{-1}$) observed in the 2011-2012 growing season when compared to the 2010-2011 growing season.

Table 6. Yield components of the winter wheat variety Fuller as affected by acidity amendment treatment during the growing seasons 2010-2011 and 2011-2012 in a Grant Silt Loam at Waukomis, OK. Yield components presented are heads per linear meter, harvest index, 100 seed weight (g), and number of seeds per spike.

| | 2010-2011 | | | | 2011-2012 | | | |
|---|---|---|---|---|---|---|---|---|
| Treatment | Heads $m^{-1}$ | HI | 100 seed wt. | Seeds $spike^{-1}$ | Heads $m^{-1}$ | HI | 100 seed wt. | Seeds $spike^{-1}$ |
| | | | g | | | | g | |
| Control | 75a† | 0.22 | 2.38 | 11 | 102 | 0.36abc | 2.86 | 27 |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 58b | 0.21 | 2.32 | 12 | 95 | 0.32c | 2.71 | 25 |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 73ab | 0.25 | 2.54 | 13 | 99 | 0.37ab | 3.02 | 28 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP‡ | 86a | 0.19 | 2.35 | 11 | 109 | 0.34bc | 2.70 | 27 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 78a | 0.2 | 2.31 | 10 | 104 | 0.34bc | 2.79 | 25 |
| 2.25 Mg $ha^{-1}$ ECCE§ | 79a | 0.19 | 2.38 | 11 | 92 | 0.36abc | 2.84 | 27 |
| 4.50 Mg $ha^{-1}$ ECCE | 81a | 0.21 | 2.31 | 12 | 90 | 0.39a | 3.04 | 30 |
| Significance | | | | | | | | |
| Rep | NS | * | NS | * | NS | *** | *** | NS |
| Treatment | * | NS | NS | NS | NS | * | NS | NS |
| Residual | | | | | | | | |
| CV (%) | 14.14 | 15.87 | 6.22 | 20.15 | 15.38 | 7.79 | 6.14 | 9.19 |

*, ***, NS Significant at P = 0.05, 0.001, and non-significant, respectively
† Identical letters in the same column indicate no significant difference at α = 0.05
‡ TSP, triple super phosphate applied with seed in furrow
§ ECCE, effective calcium carbonate equivalent

#### *4.1.2.3.2. Wheat Grain Yield and Test Weight*

There was no significant effect of acidity amendment treatment on wheat grain yield in either of the studied growing seasons (Table 7). Despite the initial drought in the 2009-2010 growing season, the better distribution of rainfall during the spring allowed yields to range from 3.09 to 3.62 Mg $ha^{-1}$. The severe drought during the spring of the 2010-2011 growing season increased differences in vegetative development among treatments; however, a freezing event on 16 April 2011 restricted wheat productivity and grain yields ranged from 1.3 to 1.65 Mg $ha^{-1}$. The yield potential in this season, calculated based on in-season NDVI measurements using data collected at wheat growth stages Feekes 4 and Feekes 5 up to the month of March (Raun et al., 2001), was significantly different among treatments, ranging from 2.69 Mg $ha^{-1}$ in the 225 kg $ha^{-1}$ $yr^{-1}$ pelletized lime to 3.62 Mg $ha^{-1}$ in the 56 kg $ha^{-1}$ $yr^{-1}$ TSP (Figure 10). This indicates that seasonal water deficit enhanced crop response to acidity amendment treatment, but the late freeze probably suppressed any difference in grain yield among treatments that would otherwise have been observed. Grain yields in the 2011-2012 growing season were higher than in the previous seasons as there was abundant rainfall. As would be expected in a wetter year, the effects of soil acidity were less apparent due to plentiful of water, and, although broadcast and incorporated lime presented mean yields slightly higher than the other treatments, the difference was not statistically significant.

Previous researches indicate that liming acid soils may not necessarily result in increased wheat grain yield (Boman et al., 1993; Caires et al., 2002; Liu et al., 2004). Results from Caires et al. (2005) indicate a yield increase in two out of 13 crops including wheat, soybean, corn, and triticale, grown in an acid soil where soil pH was increased by lime application. Liu et al. (2004) showed that in several cases wheat yield did not respond to increased soil pH due to liming, and Boman et al. (1993) found no differences in wheat yield between limed and non-limed plots in

Table 7. Effect of acidity amendment strategy on wheat grain yield (kg $ha^{-1}$) and test weight in an acid Grant Silt Loam in the growing seasons 2009-2010, 2010-2011, and 2011-2012 at Waukomis, OK

| | Growing season | | | | | |
|---|---|---|---|---|---|---|
| | 2009-2010 | | 2010-2011 | | 2011-2012 | |
| Treatment | Grain Yield | Test wt. | Grain Yield | Test wt. | Grain Yield | Test wt. |
| | kg $ha^{-1}$ | kg $hl^{-1}$ | kg $ha^{-1}$ | kg $hl^{-1}$ | kg $ha^{-1}$ | kg $hl^{-1}$ |
| Control | 3341 | 71.6cd† | 1465 | 74.4 | 4145 | 74.6 |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 3207 | 72.7abc | 1296 | 73.6 | 4031 | 74.25 |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 3379 | 71.9bcd | 1649 | 74.4 | 4256 | 74.9 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP‡ | 3619 | 73.5a | 1454 | 73.9 | 4168 | 73.5 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 3090 | 70.8d | 1526 | 73.8 | 4238 | 74.5 |
| 2.25 Mg $ha^{-1}$ ECCE§ | 3479 | 73.3ab | 1550 | 74.2 | 4376 | 75.8 |
| 4.50 Mg $ha^{-1}$ ECCE | 3303 | 72.4abc | 1640 | 73.9 | 4460 | 75.6 |
| Significance | | | | | | |
| Rep | NS | NS | * | NS | *** | *** |
| Treatment | NS | ** | NS | NS | NS | NS |
| Residual | | | | | | |
| CV (%) | 9.14 | 1.17 | 10.72 | 0.66 | 7.02 | 1.34 |

*, ***, NS Significant at P = 0.05, 0.001, and non-significant, respectively
† Identical letters in the same column indicate no statistical difference at 0.05
‡ TSP, triple super phosphate applied with seed in furrow
§ ECCE, effective calcium carbonate equivalent

Oklahoma. Scott et al. (2001) indicated that Al tolerant wheat cultivars may result in decreased grain yield when lime is applied.

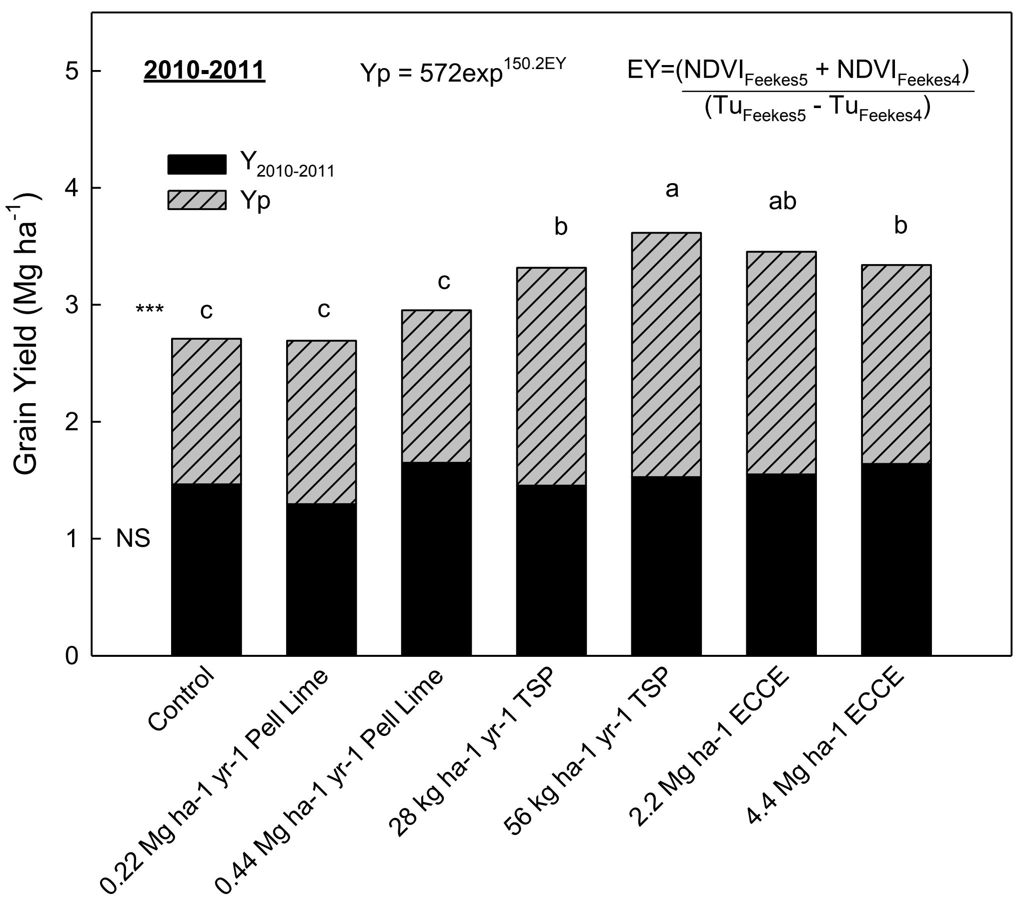


Figure 10. Yield potential (Yp) calculated based on in-season estimated grain yield (EY) computed from two post-dormancy normalized vegetative difference (NDVI) readings divided by the cumulative thermal units (°C, from Time-1 to Time-2) and measured grain yield in the 2010-2011 winter wheat growing season ($Y_{2010\text{-}2011}$) in Waukomis, OK. ***, $P < 0.001$; identical letters on the top of the bars indicate no statistical difference among grey bars; NS, difference between black bars is non-significant. Methodology and equations suggested by Raun et al. (2001).

Differences in test weight among treatments were significant in the 2009-2010 growing season (Table 7); however, values ranged from 70.8 to 73.5 kg $hl^{-1}$. No statistical difference among treatments was found in test weight in either the 2010-2011 or the 2011-2012 growing seasons.

Relative grain yield as a function of $Al_{sat}$ by year is presented in Figure 11. Banded TSP treatments were excluded from this analysis not to skew results by the confounding factor 'phosphate fertilizer'. Linear regressions derived from these relationships were non-significant, and levels of $Al_{sat}$ ranging among 0.02 and 11.37 % seemed to have little effect on wheat yields in the conditions studied. Aluminum toxicity is one of the key factors decreasing wheat yields in acid soils (Schroder et al., 2011), and fields with similar pH can result in vastly different values of $Al_{sat}$ (Johnson et al., 1997). Thus, levels of $Al_{sat}$ in the studied Grant Silt Loam may not have been high enough to induce significant differences in grain yield among treatments. Schroder et al. (2011) presented over thirty years of data of wheat grain yield affected by $Al_{sat}$, and the majority of the yields were above 80% of the control yield when $Al_{sat}$ was below 10%. Kariuki et al. (2007) presented differences in cultivar sensitivity to soil pH and $Al_{sat}$ in Oklahoma, and a detailed analysis of their data shows that decrease in wheat grain yield in several cultivars was not as accentuated at $Al_{sat} < 10\%$, although this relation was explored as linear functions from 0 to > 30 % $Al_{sat}$ by the authors. Similar linear analysis was done by Wise (2002) for winter wheat in Oklahoma, and their data shows that relative yields remained between 60 and 100% when $Al_{sat} <$ 10%.

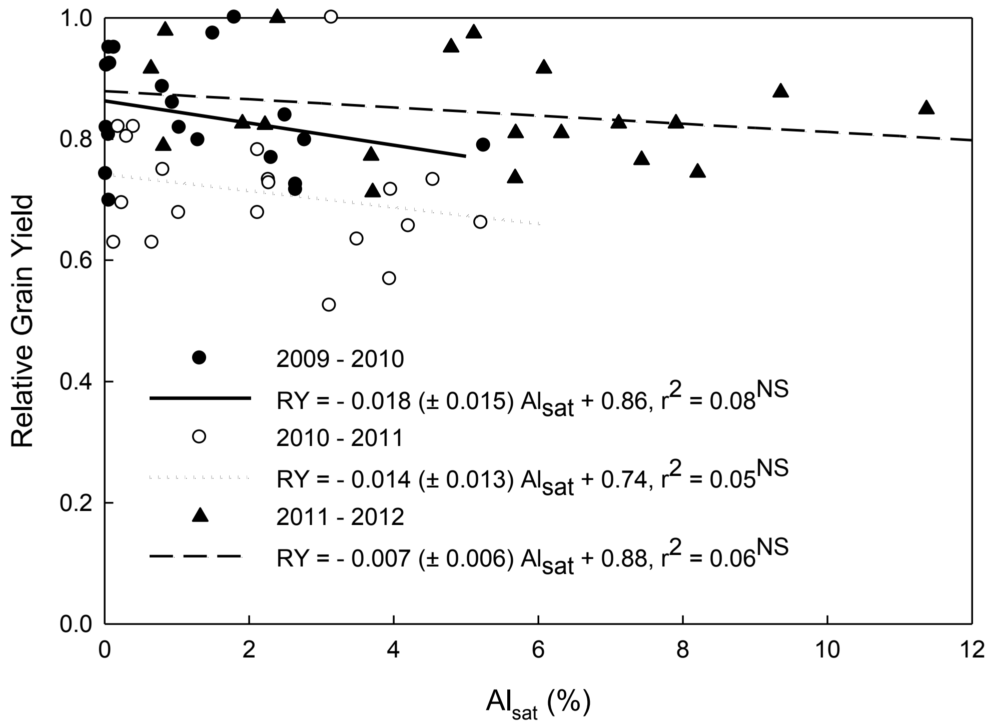


Figure 11. Relative grain yield of the winter wheat variety Fuller as a function of soil aluminum saturation (± SE) for the growing seasons 2009-2010, 2010-2011, and 2011-2012, at a Grant Silt Loam near Waukomis, OK. NS, non-significant.

#### *4.1.2.3.3. Wheat Grain Composition*

Wheat grain composition affected by acidity amendment treatment is presented in Table 8. Percent grain protein ranged from 16 to 17.7% among treatments in the 2010-2011 growing season, and banded TSP at 28 or 56 kg ha$^{-1}$ yr$^{-1}$ and broadcast agricultural lime at 2.25 or 4.50 Mg ha$^{-1}$ resulted in higher grain protein content than control or pelletized lime. The 2009-2010 and 2011-2012 growing seasons resulted in no difference in protein content among treatments. Significant differences among treatments in P and Mg contents were only observed in the 2010-2011 growing season, with no statistical differences in the remaining seasons. There were no significant differences among treatments regarding Ca or K in any of the analyzed seasons.

Table 8. Grain composition of the winter wheat variety Fuller as affected by acidity amendment treatment for the growing seasons 2009-2010, 2010-2011, and 2011-2012 in a Grant Silt Loam at Waukomis, OK. Grain components presented are percent protein, phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K).

| | 2009-10 | 2010-11 | | | | | 2011-12 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | Protein† | Protein | P‡ | Ca‡ | Mg‡ | K‡ | Protein | P | Ca | Mg | K |
| | | | | | | % | | | | | |
| Control | 14.4 | 16.3cd§ | 0.29ab | 0.045 | 0.14b | 0.39 | 15.5 | 0.27 | 0.041 | 0.14 | 0.45a |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 14.8 | 16.7cd | 0.28b | 0.049 | 0.14b | 0.37 | 15.3 | 0.29 | 0.044 | 0.14 | 0.49a |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 14.5 | 16.0d | 0.27b | 0.047 | 0.14b | 0.39 | 15.3 | 0.27 | 0.039 | 0.14 | 0.43a |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP¶ | 14.6 | 17.6ab | 0.31ab | 0.043 | 0.14b | 0.40 | 15.6 | 0.29 | 0.044 | 0.14 | 0.49a |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 14.8 | 17.7a | 0.33a | 0.043 | 0.15ab | 0.42 | 15.5 | 0.28 | 0.039 | 0.14 | 0.44a |
| 2.25 Mg $ha^{-1}$ ECCE# | 14.7 | 17.3ab | 0.33a | 0.047 | 0.16a | 0.43 | 14.9 | 0.26 | 0.037 | 0.13 | 0.41a |
| 4.50 Mg $ha^{-1}$ ECCE | 14.7 | 17.0abc | 0.28ab | 0.046 | 0.14b | 0.39 | 14.7 | 0.28 | 0.053 | 0.15 | 0.49a |
| Significance | | | | | | | | | | | |
| Rep | NS | ** | NS | * | NS | NS | *** | ** | NS | NS | * |
| Treatment | NS | ** | * | NS | * | NS | NS | NS | NS | NS | NS |
| Residual | | | | | | | | | | | |
| CV (%) | 2.83 | 3.27 | 9.94 | 7.25 | 6.46 | 7.79 | 3.29 | 8.82 | 19.5 | 8.13 | 11.35 |

*, **,***, NS Significant at P = 0.05, 0.001, 0.001, and non-significant, respectively
† Grain protein was measured using a Near Infra-Red (NIR) sensor and readings were corrected for 12% grain moisture
‡ Grain minerals P, Ca, Mg, and K, were analyzed via inductively coupled plasma-atomic emission spectroscopy (ICP) after nitric acid digestion, according to S.S.S.A. (1990).
§ Identical letters in the same column indicate no statistical difference at 0.05
¶ TSP, triple super phosphate applied with seed in furrow
# ECCE, effective calcium carbonate equivalent

### *4.1.3. Economic*

Average net returns considering the three years of the experiment for the different liming strategies are presented in Table 9. There was no significant difference among treatments when lime costs were fully assessed in the year of application; however, when lime costs were amortized over a 5-yr period the differences among treatments were significant and net returns produced by 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime rose from 9.2 and 2.1 US\$ $ha^{-1}$ $yr^{-1}$ to 12.3 and 3.8 US\$ $ha^{-1}$ $yr^{-1}$. Control and 2.25 Mg ECCE $ha^{-1}$ broadcast agricultural lime resulted in net returns greater than pelletized lime at 225 kg $ha^{-1}$ $yr^{-1}$ or 450 kg $ha^{-1}$ $yr^{-1}$. Net return from banded phosphate fertilizer did not differ significantly from the control or from pelletized lime treatments. Differences among net returns are strictly a function of differences in acidity amendment costs, because there were no significant differences in other variable input cost or grain yield among treatments. Therefore, the nontreated control treatment resulted in the highest net return as there were no acidity amendment costs, and the high price of yearly applied pelletized lime (US\$0.18 $kg^{-1}$) led to the lowest and negative return as it resulted in no increase in grain yield. Yearly application of small quantities of pelletized lime have been shown not to be cost-effective when compared to a single large application of ground agricultural lime in grass production systems in the United Kingdom (Higgins et al., 2012). Wheat budgets for 2009-2010, 2010-2011, and 2011-2012 are presented in Table A9 in the appendices for; and net return calculations as affected by liming strategies and amortization is presented in Table A10.

Negative net returns have been reported for continuous grain only wheat production systems in Oklahoma (Bushong et al., 2012; Decker et al., 2009). However, when a dual-purpose system (grazing and grain) is considered, net returns are expected to increase (Decker et al., 2009). If both forage and grain were assessed in our economic analysis, a shift in net returns would be likely to occur as banded TSP and broadcast agricultural lime increased significantly wheat canopy cover and NDVI in three and one year of the study, respectively. Both strategies could become more profitable approaches as the control produced significantly less biomass. Kaitibie et al. (2002) indicated phosphate fertilization as the optimal strategy for dual purpose wheat profitability in Oklahoma when lime costs are fully assessed in the year of application; however, broadcast agricultural lime was also an economical viable strategy when lime costs were amortized over a 5-yr period.

Table 9. Average expected returns of grain only winter wheat to acidity management strategies with lime costs fully assessed in the year of application (Lime 1-yr) or when lime costs are amortized over a five year period (Lime 5-yr) for the growing seasons of 2009-2010, 2010-2011, and 2011-2012 at Waukomis, OK.

| Treatment | Net return | |
|---|---|---|
| | Lime 1-yr† | Lime 5-yr‡ |
| | US$ $ha^{-1}$ $yr^{-1}$ | |
| Control | 8.9 | 8.9a§ |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | -22.2 | 22.2b |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | -13.9 | 13.9b |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP¶ | 1.4 | 1.4ab |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | -11.3 | 11.3ab |
| 2.25 Mg $ha^{-1}$ ECCE# | 9.2 | 12.3a |
| 4.50 Mg $ha^{-1}$ ECCE | 2.1 | 3.8ab |
| Significance | | |
| Year | *** | *** |
| Treatment | NS | * |
| Residual | | |

*, ***, NS Significant at $P$ = 0.05, 0.001, and non-significant, respectively

† Broadcast agricultural lime cost fully assessed in the year of application

‡ Broadcast agricultural lime cost amortized over a 5-yr period

§ Identical letters in the same column indicate no statistical difference at α = 0.05

¶ TSP, triple super phosphate applied with seed in furrow

# ECCE, effective calcium carbonate equivalent

### *4.2. Altus*

#### *4.2.1. Soil*

There was no significant effect of acidity amendment treatment on soil pH, Mehlich-3 extractable P or K in the Grandfield Fine Sandy Loam at Altus (Table 10). The slight changes in soil pH observed in October 2010 by broadcast incorporated lime at 4.50 Mg ECCE $ha^{-1}$ and banded pelletized lime at 450 kg $ha^{-1}$ $yr^{-1}$ were not significantly different from the control. The lack of response in soil pH to broadcast and incorporated agricultural lime is a function of the deeper incorporation of liming material, resulting from the chisel plowing of the first 40 cm of the profile. Deeper incorporation has a diluting effect on the lime particles by the subsoil, compromising lime's effectiveness in correcting soil pH (Zhang and Raun, 2006).

Table 10. Soil pH, exchangeable phosphorus and potassium as affected by soil acidity amendment strategy measured after two consecutive wheat growing seasons in a Grandfield Fine Sandy Loam at Altus, OK.

| Treatment | October 2010 | | | June 2011 | | |
|---|---|---|---|---|---|---|
| | pH | P | K | pH | P | K |
| | | mg $kg^{-1}$ | | | mg $kg^{-1}$ | |
| Control | 5.05 | 90 | 337 | 4.90 | 80 | 310 |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 5.05 | 90 | 328 | 4.98 | 84 | 319 |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 5.10 | 91 | 333 | 4.98 | 87 | 313 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP† | 4.93 | 92 | 328 | 4.90 | 86 | 308 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 4.95 | 91 | 331 | 4.88 | 83 | 303 |
| 2.25 Mg $ha^{-1}$ ECCE‡ | 5.05 | 85 | 312 | 4.98 | 59 | 301 |
| 4.50 Mg $ha^{-1}$ ECCE | 5.20 | 91 | 334 | 5.03 | 80 | 306 |
| Significance | | | | | | |
| Rep | NS | ** | ** | NS | ** | ** |
| Treatment | NS | NS | NS | NS | NS | NS |
| Residual | | | | | | |
| CV (%) | 5.28 | 10.4 | 4.97 | 2.26 | 9.53 | 4.84 |

**, NS Significant at $P = 0.01$, and non-significant

† TSP, triple super phosphate applied with seed in furrow

‡ ECCE, effective calcium carbonate equivalent, broadcast and incorporated

### *4.2.2. Wheat Crop*

#### *4.2.2.1. Canopy Cover and NDVI*

No significant differences were observed among treatments in canopy cover or NDVI the first year of the trial, in December 2008 (Table 11). A slight advantage of in canopy cover development was observed in the 2.25 and 4.50 Mg ECCE $ha^{-1}$ agricultural lime and 28 and 56 kg $ha^{-1}$ $yr^{-1}$ TSP treatments throughout the 2009-2010 growing season, with analogous NDVI behavior. Differences among treatments in NDVI, however, were not statistically significant. Broadcast agricultural lime at 2.25 or 4.50 Mg ECCE $ha^{-1}$ and 56 kg TSP $ha^{-1}$ $yr^{-1}$ also resulted in greater canopy cover in December 2010 and March 2011, and greater NDVI in December 2010, when compared to the remaining treatments. Canopy closure prior to winter dormancy averaged 25.2% among all the seasons studied, and reached a maximum of 49.2% in December 2009. Post winter dormancy canopy cover averaged 45.5% and reached 71.7% maximum in March 2010. The poorer crop development in Altus when compared to Waukomis was mainly a function of significantly lower precipitation, with totals of 376, 420, and 110 mm in the growing seasons 2008-2009, 2009-2010, and 2010-2011.

#### *4.2.2.2. Plant Population Homogeneity*

Acidity amendment strategy had no effect on NDVI CV in either of the growing seasons studied (Figure 12). Values of NDVI CV in December 2008 and throughout the growing season 2009-2010 were very close to or greater than the 17% adopted as threshold suggested by Arnall et al. (2006), indicating scattered plants and plant population density less than 100 plants $m^{-2}$. In the 2010-2011 growing season the NDVI CV was considerably lower (averaging 9.5 and 11.8% in December 2010 and March 2011), still, no statistical differences were observed among treatments. These results contrasts the results obtained at Waukomis, where banded P fertilizer increased plant population homogeneity. The soil at Altus had an average of 85 mg $kg^{-1}$ Mehlich-

Table 11. Percent canopy cover (CC) obtained via digital imagery and normalized difference vegetative index (NDVI) obtained via Greenseeker sensor as function of acidity amendment treatment measured in the growing seasons 2008-2009 (Dec-08), 2009-2010 (Dec-09 and Mar-10), and 2010-2011 (Dec-10 and Mar-11) in a Grandfield Fine Sandy Loam at Altus, OK.

| | Dec-08 | | Dec-09 | | Mar-10 | | Dec-10 | | Mar-11 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | CC | NDVI | CC | NDVI | CC | NDVI | CC | NDVI | CC | NDVI |
| | % | | % | | % | | % | | % | |
| Control | 11.6 | 0.21 | 27.5c† | 0.29 | 47.7c | 0.47 | 17.3c | 0.32b | 38.1ab | 0.46 |
| 224 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 12.4 | 0.23 | 36.3bc | 0.33 | 54.5bc | 0.52 | 17.3c | 0.32b | 26.6b | 0.42 |
| 448 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 11.0 | 0.24 | 37.1bc | 0.34 | 61.3abc | 0.52 | 22.1bc | 0.36ab | 22.1b | 0.42 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP‡ | 11.4 | 0.24 | 39.4ab | 0.33 | 60.1abc | 0.53 | 23.2bc | 0.37a | 27.1b | 0.39 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 14.2 | 0.24 | 43.5ab | 0.35 | 70.1ab | 0.65 | 29.2ab | 0.39a | 38.5ab | 0.48 |
| 2.25 Mg $ha^{-1}$ ECCE§ | 11.4 | 0.24 | 38.9b | 0.36 | 65.9ab | 0.61 | 30.5ab | 0.41a | 34.1ab | 0.44 |
| 4.50 Mg $ha^{-1}$ ECCE | 11.5 | 0.23 | 49.2a | 0.38 | 71.7a | 0.66 | 35.1a | 0.41a | 49.9a | 0.52 |
| Significance | | | | | | | | | | |
| Rep | ** | * | ** | NS | NS | NS | NS | NS | NS | NS |
| Treatment | NS | NS | ** | NS | * | NS | ** | ** | * | NS |
| Residual | | | | | | | | | | |
| CV (%) | 14.72 | 8.83 | 17.18 | 16.36 | 16.42 | 16.27 | 21.2 | 8.55 | 32.3 | 15.4 |

*, **, NS Significant at P = 0.05, 0.01, and non-significant, respectively
† Identical letters in the same column indicate no significant difference at α = 0.05
‡ TSP, triple super phosphate applied with seed in furrow
§ ECCE, effective calcium carbonate equivalent, broadcast and incorporated

3 extractable P in this experiment, which is more than 100% sufficiency for wheat crop development and yield (Zhang et al., 1998b). Thus, the benefit of additional P fertilizer was not as evident as P may not have been a restrictive factor for the wheat development in the non-fertilized treatments.

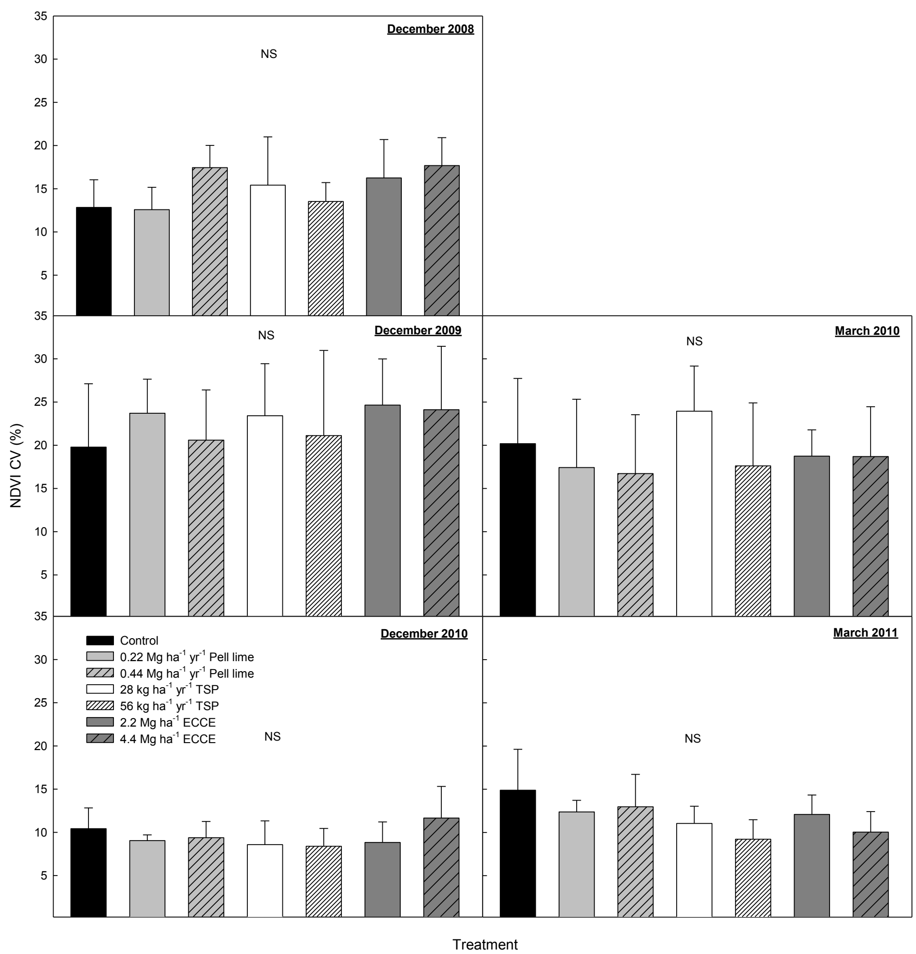


Figure 12. Mean normalized difference vegetative index coefficient of variation (NDVI CV) determined from each plot for each acidity amendment treatment prior to winter dormancy (December) and post winter dormancy prior to flowering (March), for winter wheat growing seasons 2008-2009, 2009-2010, and 2010-2011, at Altus, OK. * Significant differences among treatments for that specific month at $P$ = 0.05; NS, non-significant. Vertical error bars indicate standard deviation.

#### *4.2.2.3. Wheat Yield*

There were no significant differences among treatments in grain yield in either of the growing seasons at Altus (Table 12). Yields were slightly higher in the 2.25 or 4.50 Mg ECCE $ha^{-1}$ agricultural lime and 28 or 56 kg $ha^{-1}$ $yr^{-1}$ TSP treatments in the 2008-2009 and 2009-2010 growing seasons, but differences among treatments were non-significant. Highest grain yields were obtained in the 2009-2010 growing season, when total rainfall was 420 mm, and lowest yields were observed in the 2010-2011 growing season, when grain production was severely limited by precipitation amount (110 mm). An increase in grain yield due to liming would not be expected in this location, as soil pH was not increased by broadcast agricultural lime due to deep incorporation and dilution of liming material (Zhang and Raun, 2006).

Table 12. The effect of alternative acidity amendment strategies on wheat grain yield (kg $ha^{-1}$) grown in the growing seasons 2008-2009, 2009-2010, and 2010-2011 in a Grandfield Fine Sandy Loam at Altus, OK.

| | Growing season | | |
|---|---|---|---|
| Treatment | 2008-2009 | 2009-2010 | 2010-2011 |
| | kg $ha^{-1}$ | | |
| Control | 1948 | 2153 | 1582 |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 1752 | 2220 | 1325 |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 1685 | 2234 | 1135 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP† | 1977 | 2249 | 1214 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 2097 | 2459 | 1384 |
| 2.25 Mg $ha^{-1}$ ECCE‡ | 2109 | 2372 | 1322 |
| 4.50 Mg $ha^{-1}$ ECCE | 2004 | 2261 | 1608 |
| Significance | | | |
| Rep | NS | NS | NS |
| Treatment | NS | NS | NS |
| Residual | | | |
| CV (%) | 13.23 | 12.06 | 23.89 |

NS Non-significant
† TSP, triple super phosphate applied with seed in furrow
‡ ECCE, effective calcium carbonate equivalent

# CHAPTER V

## CONCLUSIONS

Broadcast and incorporated agricultural lime was the most effective treatment in increasing soil pH, decreasing $Al_{KCl}$ and $Al_{sat}$, and increasing soil levels of exchangeable cations. However, agricultural lime resulted in lower levels of soil extractable phosphorus at Waukomis. The effects of broadcast agricultural lime on wheat growth and development were more apparent under dry conditions, when Al toxicity symptoms were enhanced, and resulted in increased canopy cover and NDVI values when compared to the nontreated control. Banded phosphate fertilizer had no effect on soil pH or quantity or concentration of Al, but increased vegetative growth in the three seasons studied when soil extractable P was below 100% sufficiency. Pelletized lime at 450 kg $ha^{-1}$ $yr^{-1}$ resulted in slight changes in soil pH and Al in the first year of the study; however, 225 kg $ha^{-1}$ $yr^{-1}$ was not different from the control. Changes in soil pH resulting from pelletized lime were restricted to the pellet and surrounding region, with no effect on the remaining extent of the soil profile. Thus, pelletized lime behaved as large, undisturbed particles of agricultural lime. Wheat growth and development affected by pelletized lime were not different from the control, consistently presenting the lowest values of canopy cover and NDVI. No significant differences in grain yield were found among treatments as Al saturation levels were lower than 10% for most of the study. The lack of differences in grain yield led to no significant differences in net returns among treatments when broadcast incorporated agricultural lime costs were fully assessed in the year of application; however, pelletized lime had a very high price per unit and resulted in the lowest net return when broadcast agricultural lime costs were amortized over a 5-yr period.

# REFERENCES

Álvarez, E., A. Viade, M.L. Fernandez-Marcos. 2009. Effect of liming with different sized limestone on the forms of aluminum in a Galician soil (NW Spain). Geoderma 152:1-8.

Anjos, J.T., and D.L. Rowell. 1987. The effect of lime on phosphorus adsorption and barley growth in three acid soils. Plant Soil 103:75-82.

Arnall, D.B., W.R. Raun, J.B. Solie, M.L. Stone, G.V. Johnson, K. Girma, K.W. Freeman, R.K. Teal, and K.L. Martin. 2006. Relationship between coefficient of variation measured by spectral reflectance and plant density at early growth stages in winter wheat. J. Plant Nutr. 29:1983-1997.

Bertsch, P.M., and P.R. Bloom. 1996. Aluminum. P 517-550. In D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Blevins, R.L., L.W. Murdock, and G.W. Thomas. 1978. Effect of lime application on no-tillage and conventionally tilled corn. Agron. J. 70:322-326.

Bohn, H.L., B.L. McNeal, and G.A. O'Connor. 2001. Soil Chemistry. 3rd Ed. by John Wiley & Sons, New York, NY.

Boman, R.K., W.R. Raun, and E.G. Krenzer. 1993. Effects of soil pH on yield of winter wheat. p. 75-77. *In* W.R. Raun et al. (ed.) Soil fertility research highlights. Okla. St. Univer. Stillwater, OK.

Boman, R.K., R.L. Westerman, G.V. Johnson, and M.E. Jojola. 1992. Phosphorus fertilization effects on winter wheat production in acid soils. P. 171-174. *In* R.L. Westerman (ed.) Efficient use of fertilizers. Agron. 92-1. Okla. Agric. Exp. Stn., Stillwater.

Bushong, J.A., A.P. Griffith, T.F. Peeper, and F.M. Epplin. 2012. Continuous winter wheat versus a winter canola-winter wheat rotation. Agron. J. 104:324-330.

Buthcee, J.D. Effect of simulated grazing intensity on dual purpose winter wheat (Triticum aestivum L.) grain yield in Oklahoma. M.S. Thesis. Oklahoma State Univ., Stillwater.

Caires, E.F., G. Barth, and F.J. Garbuio. 2006. Lime application in the establishment of a no-till system for grain crop production in Southern Brazil. Soil Till. Res. 89:3-12.

Caires, E.F., L.R.F. Alleoni, M.A. Cambri, and G. Barth. 2005. Surface application of lime for crop grain production under a no-till system. Agron. J. 97:791-798.

Caires, E.F., I.C. Feldhaus, G. Barth, and F.J. Garbuio. 2002. Lime and gypsum application on the wheat crop. Scient. Agric. 59:357-364.

Christensen, N.W., R.L. Powelson, and M. Brett. 1987. Epidemiology of wheat take-all as influenced by soil pH and temporal changes in inorganic soil N. Plant Soil. 98:221-230.

Conte, E., I. Anghinoni, and D.S. Rheinheimer. 2003. Phosphorus accumulation fractions in a clayey oxisol in relation to phosphate doses under no-tillage. Rev. Bras. Cien. Solo 27:893-900.

Coventry, D.R., T.G. Reeves, H.D. Brooke, A. Ellington, and E.J. Slattery. 1987. Increasing wheat yields in north-eastern Victoria by liming and deep ripping. Aust. J. Exp. Agric. 27:679-685.

Curtin, D., and J.K. Syers. 2001. Lime-induced changes in indices of soil phosphate availability. Soil Sci. Soc. Am. J. 65:147-152.

Decker, J.E., F.M. Epplin, D.L. Morley, and T.F. Peeper. 2009. Economics of five wheat production systems with no-till and conventional tillage. Agron. J. 101:364-372.

Edwards, J.T., R.M. Hunger, E.L. Smith, G.W. Horn, M.S. Chen, L. Yan, G. Bai, R.L. Bowden, A.R. Klatt, P. Rayas-Duarte, R.D. Osburn, K.L. Giles, J.A. Kolmer, Y. Jin, D.R. Porter, B.W. Seabourn, M.B. Bayles, and B.F. Carver. 2012. 'Duster' wheat: a durable, dual-purpose cultivar adapted to the Southern Great Plains of the USA. J. Plant Regist. 6:37-48.

Ernani, P.R., C. Bayer, and L. Maestri. 2002. Corn yield as affected by liming and tillage system on an acid Brazilian Oxisol. Agron. J. 94:305-309.

Fageria, N.K., L.F. Stone. 2006. Physical, chemical, and biological changes in the rizhosphere and nutrient availability. J. Plant Nutr., 29: 7, 1327-1356.

Fageria, N.K., F.J.P. Zimmermann. 1998. Influence of pH on growth and nutrient uptake by crop species in an Oxisol. Commun. Soil Sci. Plant Anal. 29:17, 2675-2682.

FAO. 2012. Food and Agricultural Organization of the United Nations, Rome, Italy. FAOSTAT. Available at http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor (accessed 10 June 2012; verified 27 July 2012).

Fritz, A.K., T.J. Martin, and J.P. Shroyer. 2007. Fuller hard red wheat. Kansas St. Univ. Ag. Exp. Sta. and coop. Ext. Serv. L-927. Kansas St. Univer., Manhattan.

Godsey, C.B., G.M. Pierzynski, D.B. Mengel, and R.E. Lamond. 2007. Changes in soil pH, organic carbon, and extractable aluminum from crop rotation and tillage. Soil Sci. Soc. Am. J. 71:1038-1044.

Guertal, E.A., and R.L. Westerman. 1992. Changes in phosphorus, aluminum and manganese in three acid-affected soils amended with phosphorus. Agronomy Report 92-1. Okla. Agr. Exp. Sta., Okla. St. Univer., Stillwater.

Haling, R.E., R.J. Simpson, E. Delhaize, P.J. Hocking, and A.E. Richardson. 2010. Effect of lime on root growth, morphology and the rhizosheath of cereal seedlings growing in an acid soil. Plant Soil 327:199-212.

Haynes, R.J. 1982. Effects of liming on phosphate availability in acid soils. A critical review. Plant Soil. 68:289-308.

Higgins, S., S. Morrison, and C.J. Watson. 2012. Effect of annual applications of pelletized dolomitic lime on soil chemical properties and grass productivity. Soil Use Manage. 28:62-69.

Ingram, D. L., and C. R. Johnson. 1982. Effects of liming source and rate on container media pH. Proc. Fla. State Hort. Soc. 95:156-157.

Johnson J.P., B.F. Carver, and V.C. Baligar. 1997. Productivity in Great Plains acid soils of wheat genotypes selected for aluminium tolerance. Plant Soil 188:101-106.

Johnson, G.V., R.L. Westerman, E. Allen, and R. Boman. 1991. Managing acid soils for wheat production. Okla. St. Univer. Ext. Facts F-2240. Okla. St. Univer., Stillwater.

Jonhson, G.V., H. Zhang. Cause and effects of soil acidity. 2009. Okla. St. Univer. Ext. Facts F-2239. Okla. St. Univer., Stillwater.

Kaitibie, S., F.M. Epplin, E.G. Krenzer Jr., H. Zhang. 2002. Economics of lime and phosphorus application for dual-purpose wheat production in low-pH soils. Agron. J. 94:1139-1145.

Karuiki, S.K., H. Zhang, J.L. Schroder, J. Edwards, M. Payton, B. Carver, W.R. Raun, and E.G. Krenzer. 2007. Hard red winter wheat cultivar responses to a pH and aluminum concentration gradient. Agron. J. 99:88-98.

Kauffman, M.D., and E.H. Gardner. 1978. Segmental liming of soil and its effect on the growth of wheat. Agron. J. 70:331-336.

Kochian, L., O.A. Hoekenga, and M.A. Piñeros. 2004. How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. Annu. Rev. Plant Bio. 55:459-493.

Krizek, D.T., and C.D. Foy. 1988. Role of water-stress in differential aluminum tolerance of 2 barley cultivars grown in an acid soil. J. Plant Nutr. 11:351-367.

Krizek, D.T., C.D. Foy, and W.P. Wergin. 1988. Role of water-stress in differential aluminum tolerance of 6 sunflower cultivars grown in an acid soil. J. Plant Nutr. 11:387-408.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Lentz, E.M., K.A. Diedrick, C.E. Dygert, D.C. Henry, and R.W. Mullen. 2010. Soil pH and corn grain yield response to low rates of pelletized and typical ag-lime. J. of Natio. Assoc. of County Agri. Ag. Available at www.nacaa.com/journal/index.php?jid=56. (accessed 06 July 2011).

Lidon, F.C., H.G. Azinheira, and M.G. Barreiro. 2000. Al toxicity in maize: modulation of biomass production and nutrients uptake and translocation. J. Plant Nut. 23:151-160.

Liu, D.L., K.R. Helyar, M.K. Conyers, R. Fisher, G.J. Poile. 2004. Response of wheat, triticale and barley to lime application in semi-arid soils. Field Crops Res. 90:287-301.

Lukin, V.V., F.M. Epplin. 2003. Optimal frequency and quantity of agricultural lime applications. Agri. Syst. 76:949-967.

MacNish, G.C. 1988. Changes in take-all (*Gaeumannomyces graminis* var. *tritici*), rhizoctonia root rot (*Rhizoctonia solani*) and soil pH in continuous wheat with annual applications of nitrogenous fertiliser in western Australia. Aust. J. of Exp. Agric. 28:333-341.

Mahler, R.L., and R.E. McDole. 1987. Effect of soil pH on crop yield in Northern Idaho. Agron. J. 79:751-755.

Marschner, H. 1991. Mechanisms of adaptation of plants to acid soils. Plant Soil. 134:1-20.

Martin, K.L., K. Girma, K.W. Freeman, R.K. Teal, B. Tubana, D.B. Arnall, B. Chung, O. Walsh, J.B. Solie, M.L. Stone, and W.R. Raun. 2007. Expression of variability in corn as influenced by growth stage using optical sensor measurements. Agron. J. 99:384-389.

Mccollum, R.E. 1991. Buildup and decline in soil-phosphorus - 30-year trends on a Typic Umprabuult. Agron. J. 83:77-85.

McMaster, G.S., and Wilhelm, W.W. 2010. The wheat plant – Development, growth, and yield. In F.B. Peairs & R. Armenta (Eds.), Wheat production and pest management for the Great Plains region (p. 7-16). Colorado St. Univer. Ext. XCM235. Color. St. Univer., Fort Collins.

Morris, K.B., K.L. Martin, K.W. Freeman, R.K. Teal, K. Girma, D.B. Arnall, P.J. Hodgen, J. Mosali, W.R. Raun, and J.B. Solie. 2006. Mid-season recovery from nitrogen stress in winter wheat. J. Plant Nutr. 29:727-745.

Murdock, L.W. 1997. Pelletized lime – how quickly does it react? Soil Sci. News and Views 18(9). Univer. of Kent., Lexington.

Murrmann, R.P., and M. Peech. 1969. Effect of pH on labile and soluble phosphate in soils. Soil Sci. Soc. Am. J. 33:205-210.

NASS. 2012a. National Agricultural Statistics Service. Oklahoma wheat county estimates. Available at http://www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/County_Estimates/2012/ok_wheat_county_estimates_2011.pdf (accessed 11 July 2012; verified 27 July 2012).

NASS. 2012b. National Agricultural Statistics Service. Agricultural prices. Available at http://usda01.library.cornell.edu/usda/current/AgriPric/AgriPric-06-28-2012.pdf (accessed 10 May 2012; verified 27 July 2012).

Nye, P.H. 1981. Changes of pH across the rhizosphere induced by roots. Plant Soil. 61:7 - 26.

Pavan, M.A., F.T. Bingham, and P.F. Pratt. 1984. Redistribution of exchangeable calcium, magnesium, and aluminum following lime or gypsum applications to a Brazilian Oxisol. Soil Sci. Soc. Am. J. 48:33-38.

Phillips, S.B., W.R. Raun, G.V. Johnson, and W.E. Thomason. 2000. Effect of dual applied phosphorus and gypsum on wheat forage and grain yield. J. Plant Nutr. 23:251-261.

Pierce, F.J., and D.D. Warncke. 2000. Soil and crop response to variable-rate liming for two Michigan fields. Soil Sci. Soc. Am. J. 64:774-780.

Purcell, L.C. 2000. Soybean canopy coverage and light interception measurements using digital imagery. Crop Sci. 40:834-837.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131-138.

Rodríguez, D., F.H. Andrade, and J. Goudriaan. 1999. Effects of phosphorus nutrition on tiller emergence in wheat. Plant Soil 209:283-295.

Rodríguez, D., F.H. Andrade, and J. Goudriaan. 2000. Does assimilate supply limit leaf expansion in wheat grown in the field under low phosphorus availability? Field Crops Res. 67:227-238.

Rodríguez, D., W.G. Keltjens, and J. Goudriaan J. 1998. Plant leaf area expansion and assimilate production in wheat (Triticum aestivum L.) growing under low phosphorus conditions. Plant Soil 200:227-240.

Ruiz-Torres, N.A., B.F. Carver, and R.L. Westermann. 1992. Agronomic performance in acid soils of wheat lines selected for hematoxylin staining pattern. Crop Sci. 32:104-107.

Samac, D.A., and M. Tesfaye. 2003. Plant improvement for tolerance to aluminum in acid soils - a review. Plant Cell Tissue Organ Cult. 75:189-207.

Sandaña, P., D. Pinochet. 2011. Ecophysiological determinants of biomass and grain yield of wheat under P deficiency. Field Crops Res. 120:311-319.

Sandaña, P., M. Ramirez, and D. Pinochet. 2012. Radiation interception and radiation use efficiency of wheat and pea under different P availabilities. Field Crops Res. 127:44-50.

Sander, D.H., and B. Eghball. 1999. Planting date and phosphorus fertilizer placement effects on winter wheat. Agron. J. 91:707-712.

SAS Institute. 2004. SAS/STAT: Procedures. SAS Proprietary Software Release 9.2. SAS Inst., Cary, NC.

Sato, A., A. Oyanagi, and M. Wada. 1996. Effect of phosphorus content on the emergence of tillers in wheat cultivars. Jarq-Jpn. Agric. Res. Quart. 30:27-30.

Schroder, J.L., H.L. Zhang, K. Girma, W.R. Raun, C.J. Penn, and M.E. Payton. 2011. Soil acidification from long-term use of nitrogen fertilizers on winter wheat. Soil Sci. Soc. Am. J. 75:957-964.

Scott, B.J., M.K. Conyers, G.J. Poile, and B.R. Cullis. 1997. Subsurface acidity and liming affect yield of cereals. Aust. J. Agric. Res. 48:843-854.

Scott, B.J., and N.E. Coombes. 2006. Poor incorporation of lime limits grain yield response in wheat. Aust. J. Exp. Agric. 46:1481-1487.

Scott, B.J., J.A. Fisher, and B.R. Cullis. 2001. Aluminium tolerance and lime increase wheat yield on the acidic soils of central and southern New South Wales. Aust. J. of Exp. Agric. 41:523-532.

SERA-IEG-7 (Southern Extension Research Activity-Information Exchange Group-6). 2001. Procedures used by State soil testing laboratories in the Southern region of the United States. Bull. 190-C. SW Florida Res. Educ. Ctr., Immokalee, FL.

Sloan, J.J., N.T. Basta N.T., and R.L. Westerman. 1995. Aluminum transformations and solution equilibria induced by banded phosphorus-fertilizer in acid soil. Soil Sci. Soc. Am. J. 59:357-364.

Smiley, R.W., and R.J. Cook. 1973. Relationship between take-all of wheat and rhizosphere pH in soils fertilized with ammonium vs. nitrate-nitrogen. Phytopathology 63:882-890.

Soil Science Society of America. 1990. Soil testing and plant analysis. 3rd Ed. pp. 404-411.

Spies, C.D., and C.L. Harms. 2007. Soil acidity and liming of Indiana soils. Purdue Univer. Coop. Ext. Ser. Document AY-267. West Lafayette, IN.

Staton, M., and D. Warncke. 2006. Pelletized lime in Michigan. Crop and Soil Sci. Inf. Ser., Michig. St. Univer., East Lansing.

Sumner, M.E., and W.P. Miller. 1996. Cation exchange capacity and exchange coefficients. p. 1201-1253. In D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Systat Software. 2004. SigmaPlot for Windows. Version 9. Systat Software, Point Richmond, CA.

Tang, C., Z. Rengel, E. Diatloff, C. Gazey. 2002. Responses of wheat and barley to liming on a sandy soil with subsoil acidity. Field Crops Res. 80:234-244.

Tang, C., Z. Rengel, E. Diatloff, and C. Gazey. 2003. Responses of wheat and barley to liming on a sandy soil with subsoil acidity. Field Crops Res. 80:235-244.

Thomas, G.W. 1996. Soil pH and soil acidity. p. 475-490. In D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. ASA and SSSA, Madison, WI.

Westermann, D.T. 1992. Lime effects on phosphorus availability in a calcareous soil. Soil Sci. Soc. Am. J. 56:489-494.

Wise, K. 2002. Impact of soil acidity on crop production. M.S. Thesis. Oklahoma State Univ., Stillwater.

USDA. 2010. United States Department of Agriculture. 2010 State Agriculture Overview – Oklahoma. Available at http://www.nass.usda.gov/Statistics_by_State/Ag_Overview/AgOverview_OK.pdf (accessed 17 June 2011; verified 27 July 2012).

USDA. 2012. United States Department of Agriculture. 2012 Crop Production. Available at http://www.usda.gov/nass/PUBS/TODAYRPT/crop0712.pdf (accessed 11 July 2012; verified 27 July 2012).

Valle, S.R., D. Pinochet, and D.F. Calderini. 2009. Al toxicity effects on radiation interception and radiation use efficiency of Al-tolerant and Al-sensitive wheat cultivars under field conditions. Field Crops Res. 114:343-350.

von Uexküll, H.R., and E. Mutert. 1995. Global extent, development and economic-impact of acid soils. Plant Soil 171:1-15.

Zhang, H. 2001. Fertility of Oklahoma agricultural soils. Better Crops 85:19-20.

Zhang, T.Q., A.F. MacKenzie, B.C. Liang, and C.F. Drury. 2004. Soil test phosphorus and phosphorus fractions with long-term phosphorus addition and depletion. Soil Sci. Soc. Am. J. 68:519-528.

Zhang, H., J. Edwards, B. Carver, and B. Raun. 2010. Managing acid soils for wheat production. Okla. St. Univer. Ext. Facts F-2240. Okla. St. Univer., Stillwater.

Zhang, H., B. McCray. 2009. Oklahoma Agricultural Soil Test Summary 2004-2008. Okla. St. Univer. Ext. Facts F-2259. Okla. St. Univer., Stillwater.

Zhang, H., G.V. Johnson, G. Krenzer, and R. Gribble. 1998a. Soil testing for an economically and environmentally sound wheat production. Commun. Soil Sci. Plant Anal. 29:1707-1717.

Zhang, H., G.V. Johnson, W.R. Raun, N.T. Basta, and J.A. Hattey. 1998b. OSU Soil test interpretations. Okla. St. Univer. Ext. Facts F-2225. Okla. St. Univer., Stillwater.

Zhang, H., and W.R. Raun. 2006. Oklahoma soil fertility handbook. Dept. of Plant and Soil Sciences, Okla. St. Univer., Stillwater, OK.

# APPENDICES

Table A1. Soil type and initial conditions prior to study establishment in Altus and Waukomis, OK.

| | Altus | Waukomis |
|---|---|---|
| Soil type | Grandfield Fine Sandy Loam (fine-loamy, mixed, superactive, thermic Typic Haplustalfs) | Grant Silt Loam (fine-silty, mixed, superactive, thermic Udic Argiustolls) |
| Date | Oct-08 | Aug-09 |
| pH | 4.8 | 4.9 |
| Buffer Index | 6.9 | 6.8 |
| NO3-Nitrogen (ppm) | 16 | 11.5 |
| Mehlich-3 P (ppm) | 86.5 | 23.5 |
| Mehlich-3 K (ppm) | 327 | 198.5 |

Table A2. Ground and pelletized lime chemical characteristics.

| | Ground lime | Pelletized lime |
|---|---|---|
| | % | |
| Moisture | 2.7 | 0.8 |
| pH | 9.4 | 8.2 |
| Ca | 30.3 | 28.4 |
| Mg | 3.7 | 10.3 |
| K | 0.1 | 0.1 |
| S | 0.3 | 0.7 |

Table A3. Comparison between previous low-rate agricultural lime study and the present study for Waukomis, OK.

| | Higgins et al. (2012) Soil pH† | | Waukomis, OK Soil pH‡ | | | |
|---|---|---|---|---|---|---|
| Lime rate | Initial mean | Final mean§ | Initial mean | Final mean¶ | Change in pH | Significance# |
| kg $ha^{-1}$ $yr^{-1}$ | | | | | | |
| 0 | 5.72 | 5.75 | | | 0.03 | * |
| 175 | 5.74 | 5.81 | | | 0.07 | *** |
| 350 | 5.73 | 5.88 | | | 0.15 | *** |
| 525 | 5.70 | 5.95 | | | 0.25 | *** |
| 0 | | | 4.90 | 4.90 | 0.00 | NS |
| 220 | | | 4.90 | 5.00 | 0.10 | NS |
| 440 | | | 4.90 | 5.08 | 0.18 | *** |
| 2200†† | | | 4.90 | 5.90 | 1.00 | *** |
| 4400†† | | | 4.90 | 5.60 | 0.70 | *** |

*, ***, NS Significant at P < 0.5, P < 0.001, and non-significant, respectively

† Soil pH measured in a 1 : 2.5 soil / water solution

‡ Soil pH measured in a 1 : 1 soil / water solution

§ Final mean measured approximately 21 months after first lime application

¶ Final mean measured approximately 12 months after first lime application

\# Significance for Higgins et al. (2012) was calculated individually for several depth segments in the soil profile and the predominant result for the whole profile is being reported. For Waukomis the significance is based on statistical difference from the control treatment after the first year of the trial

†† Total rate applied at a single application, not yearly as the remaining treatments

.

Table A4. Soil pH across the profile measured at different points (1 – 32, Figure 1) evenly spaced from the lime pellet at unequal intervals after the 2010 – 2011 and 2011 – 2012 wheat growing seasons for a Grant Silt Loam at Waukomis, OK.

| | 2010 - 2011 | | | | | 2011 - 2012 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pell Lime | | Broadcast Lime | | | Pell Lime | | Broadcast Lime | |
| Point | Control | 220† | 440† | 2.25‡ | 4.50‡ | Control | 220 | 440 | 2.25 | 4.50 |
| | Measured soil pH | | | | | | | | | |
| 1 | 4.31$^{efghij§}$ | 4.30$^{defg}$ | 4.30$^{ef}$ | 4.81$^{efg}$ | 5.19$^{cdef}$ | 3.95$^{f}$ | 3.98$^{f}$ | 4.51$^{fghi}$ | 4.57$^{cdef}$ | 4.77$^{defg}$ |
| 2 | 4.23$^{efghij}$ | 4.36$^{defg}$ | 4.42$^{def}$ | 5.00$^{cdef}$ | 5.34$^{bcd}$ | 4.00$^{f}$ | 3.98$^{f}$ | 4.44$^{ghi}$ | 4.58$^{abcdef}$ | 4.81$^{cdefg}$ |
| 3 | 4.40$^{efgh}$ | 4.58$^{defg}$ | 4.45$^{def}$ | 5.20$^{cde}$ | 5.30$^{cd}$ | 4.12$^{f}$ | 3.95$^{f}$ | 4.43$^{hi}$ | 4.44$^{def}$ | 4.76$^{efg}$ |
| 4 | 4.47$^{efgh}$ | 4.29$^{defg}$ | 4.49$^{cdef}$ | 5.10$^{cdef}$ | 5.34$^{bcd}$ | 4.10$^{f}$ | 4.14$^{ef}$ | 4.60$^{efghi}$ | 4.55$^{cdef}$ | 5.37$^{abcdefg}$ |
| 5 | 4.72$^{de}$ | 4.62$^{defg}$ | 4.85$^{bcdef}$ | 5.79$^{abcd}$ | 5.81$^{abcd}$ | 4.15$^{f}$ | 4.24$^{cdef}$ | 5.03$^{bcdefghi}$ | 4.64$^{abcdef}$ | 5.11$^{abcdefg}$ |
| 6 | 4.54$^{efg}$ | 5.35$^{c}$ | 5.27$^{abcd}$ | 5.84$^{abc}$ | 6.13$^{abc}$ | 5.30$^{abc}$ | 4.29$^{cdef}$ | 5.99$^{a}$ | 4.83$^{abcde}$ | 5.25$^{abcdefg}$ |
| 7 | 4.41$^{efgh}$ | 4.81$^{d}$ | 5.02$^{bcde}$ | 5.37$^{cde}$ | 5.12$^{cdefg}$ | 5.34$^{ab}$ | 4.26$^{cdef}$ | 5.37$^{abcdefg}$ | 4.67$^{abcdef}$ | 5.14$^{abcdefg}$ |
| 8 | 4.42$^{efgh}$ | 4.36$^{defg}$ | 4.70$^{bcdef}$ | 4.88$^{efg}$ | 5.52$^{abcd}$ | 4.53$^{bcdef}$ | 4.29$^{cdef}$ | 4.77$^{defghi}$ | 4.55$^{cdef}$ | 5.16$^{abcdefg}$ |
| 9 | 4.38$^{efgh}$ | 4.37$^{defg}$ | 4.76$^{bcdef}$ | 4.98$^{def}$ | 5.52$^{abcd}$ | 4.18$^{f}$ | 4.21$^{cdef}$ | 4.57$^{efghi}$ | 4.50$^{cdef}$ | 5.24$^{abcdefg}$ |
| 10 | 4.26$^{efghij}$ | 4.35$^{defg}$ | 4.74$^{bcdef}$ | 5.08$^{cdef}$ | 5.56$^{abcd}$ | 4.15$^{f}$ | 4.20$^{cdef}$ | 4.44$^{ghi}$ | 4.54$^{cdef}$ | 5.23$^{abcdefg}$ |
| 11 | 4.20$^{efghij}$ | 4.44$^{defg}$ | 4.63$^{cdef}$ | 4.89$^{efg}$ | 5.45$^{abcd}$ | 4.31$^{def}$ | 4.27$^{cdef}$ | 4.57$^{efghi}$ | 4.79$^{abcdef}$ | 5.36$^{abcdefg}$ |
| 12 | 5.37$^{bc}$ | 5.43$^{c}$ | 5.56$^{ab}$ | 5.49$^{cde}$ | 5.99$^{abcd}$ | 4.52$^{bcdef}$ | 4.47$^{bcdef}$ | 4.67$^{defghi}$ | 5.11$^{a}$ | 5.48$^{abcdef}$ |
| 13 | 5.13$^{cd}$ | 5.38$^{c}$ | 5.27$^{abcd}$ | 5.58$^{bcde}$ | 6.11$^{abc}$ | 4.56$^{bcdef}$ | 4.39$^{bcdef}$ | 5.33$^{abcdefgh}$ | 4.93$^{abcd}$ | 5.55$^{abcd}$ |
| 14 | 4.27$^{efghij}$ | 4.66$^{defg}$ | 4.81$^{bcdef}$ | 5.20$^{cde}$ | 5.51$^{abcd}$ | 4.76$^{abcdef}$ | 4.31$^{cdef}$ | 5.26$^{abcdefghi}$ | 4.78$^{abcdef}$ | 5.32$^{abcdefg}$ |
| 15 | 4.19$^{efghij}$ | 4.26$^{defg}$ | 4.48$^{cdef}$ | 5.03$^{cdef}$ | 5.75$^{abcd}$ | 4.39$^{def}$ | 4.23$^{cdef}$ | 4.82$^{cdefghi}$ | 4.66$^{abcdef}$ | 5.33$^{abcdefg}$ |
| 16 | 4.01$^{fghij}$ | 4.09$^{efg}$ | 4.55$^{cdef}$ | 5.10$^{cdef}$ | 5.97$^{abcd}$ | 4.29$^{ef}$ | 4.19$^{def}$ | 4.56$^{efghi}$ | 4.49$^{def}$ | 5.81$^{a}$ |
| 17 | 3.68$^{j}$ | 4.07$^{fg}$ | 4.29$^{ef}$ | 4.82$^{efg}$ | 5.24$^{cde}$ | 4.15$^{f}$ | 4.16$^{ef}$ | 4.38$^{i}$ | 4.31$^{ef}$ | 5.23$^{abcdefg}$ |
| 18 | 4.00$^{fghij}$ | 4.07$^{fg}$ | 4.07$^{f}$ | 4.30$^{fg}$ | 4.27$^{efg}$ | 4.09$^{f}$ | 4.41$^{bcdef}$ | 4.40$^{hi}$ | 4.45$^{def}$ | 4.83$^{cdefg}$ |
| 19 | 6.46$^{a}$ | 6.61$^{a}$ | 6.06$^{a}$ | 6.33$^{ab}$ | 6.50$^{a}$ | 5.20$^{abcd}$ | 5.41$^{a}$ | 5.47$^{abcde}$ | 4.94$^{abcd}$ | 5.54$^{abcde}$ |
| 20 | 5.33$^{bc}$ | 6.16$^{ab}$ | 5.99$^{a}$ | 6.43$^{a}$ | 6.43$^{ab}$ | 5.51$^{a}$ | 4.64$^{bcde}$ | 5.81$^{ab}$ | 5.04$^{abc}$ | 5.14$^{abcdefg}$ |
| 21 | 4.34$^{efghi}$ | 4.70$^{def}$ | 5.02$^{bcde}$ | 5.11$^{cdef}$ | 6.03$^{abc}$ | 5.14$^{abcde}$ | 4.52$^{bcde}$ | 5.39$^{abcdef}$ | 4.81$^{abcdef}$ | 5.23$^{abcdefg}$ |
| 22 | 4.19$^{efghij}$ | 4.64$^{defg}$ | 4.67$^{cdef}$ | 5.10$^{cdef}$ | 6.01$^{abcd}$ | 4.55$^{bcdef}$ | 4.52$^{bcde}$ | 4.93$^{bcdefghi}$ | 4.70$^{abcdef}$ | 5.25$^{abcdefg}$ |
| 23 | 3.90$^{ghij}$ | 4.20$^{defg}$ | 4.80$^{bcdef}$ | 5.03$^{cdef}$ | 5.40$^{abcd}$ | 4.30$^{def}$ | 4.26$^{cdef}$ | 4.55$^{fghi}$ | 4.59$^{abcdef}$ | 5.58$^{abc}$ |
| 24 | 4.00$^{fghij}$ | 4.17$^{efg}$ | 4.18$^{ef}$ | 4.34$^{fg}$ | 4.20$^{fg}$ | 4.31$^{def}$ | 4.53$^{bcde}$ | 4.51$^{fghi}$ | 4.53$^{cdef}$ | 4.69$^{fg}$ |
| 25 | 4.26$^{efghij}$ | 4.44$^{defg}$ | 4.24$^{ef}$ | 4.16$^{g}$ | 4.15$^{g}$ | 4.47$^{bcdef}$ | 4.82$^{b}$ | 4.74$^{defghi}$ | 4.65$^{abcdef}$ | 4.75$^{fg}$ |
| 26 | 5.79$^{b}$ | 5.73$^{bc}$ | 5.36$^{abc}$ | 5.75$^{abcd}$ | 6.17$^{abc}$ | 4.43$^{cdef}$ | 4.66$^{bcde}$ | 5.55$^{abcd}$ | 5.10$^{ab}$ | 5.43$^{abcdef}$ |
| 27 | 5.50$^{bc}$ | 5.54$^{c}$ | 5.05$^{bcde}$ | 5.83$^{abcd}$ | 6.14$^{abc}$ | 4.75$^{abcdef}$ | 4.42$^{bcdef}$ | 5.73$^{abc}$ | 4.78$^{abcdef}$ | 5.08$^{abcdefg}$ |
| 28 | 4.59$^{def}$ | 4.72$^{de}$ | 4.99$^{bcde}$ | 5.20$^{cde}$ | 5.92$^{abcd}$ | 4.37$^{def}$ | 4.71$^{bc}$ | 5.23$^{abcdefghi}$ | 4.70$^{abcdef}$ | 5.29$^{abcdefg}$ |
| 29 | 4.31$^{efghij}$ | 4.32$^{defg}$ | 4.91$^{bcdef}$ | 5.08$^{cdef}$ | 5.86$^{abcd}$ | 4.31$^{def}$ | 4.70$^{bcd}$ | 4.98$^{bcdefghi}$ | 4.57$^{bcdef}$ | 5.30$^{abcdefg}$ |
| 30 | 4.36$^{efgh}$ | 4.15$^{efg}$ | 4.88$^{bcdef}$ | 5.25$^{cde}$ | 6.00$^{abcd}$ | 4.25$^{ef}$ | 4.16$^{ef}$ | 5.11$^{abcdefghi}$ | 4.45$^{def}$ | 5.71$^{ab}$ |
| 31 | 3.89$^{hij}$ | 4.03$^{g}$ | 4.31$^{ef}$ | 4.98$^{def}$ | 4.93$^{defg}$ | 4.13$^{f}$ | 4.16$^{ef}$ | 4.43$^{hi}$ | 4.27$^{f}$ | 5.01$^{bcdefg}$ |
| 32 | 3.71$^{ij}$ | 4.13$^{efg}$ | 4.54$^{cdef}$ | 4.27$^{fg}$ | 4.22$^{fg}$ | 4.13$^{f}$ | 4.46$^{bcdef}$ | 4.38$^{i}$ | 4.48$^{def}$ | 4.61$^{g}$ |
| Significance | | | | | | | | | | |
| Rep | ** | *** | ** | NS | ** | *** | NS | *** | *** | *** |
| Treatment | *** | *** | *** | *** | *** | *** | *** | *** | * | * |
| Residual | | | | | | | | | | |
| CV (%) | 8.32 | 7.84 | 10.69 | 9.46 | 11.34 | 11.8 | 6.76 | 10.92 | 6.7 | 8.63 |

*, **, ***, NS Significant at P = 0.05, 0.01, and 0.001, and non-significant

† Rate of pelletized lime applied, kg ha$^{-1}$ yr$^{-1}$

‡ Rate of lime broadcast and incorporated, Mg ECCE ha$^{-1}$

§ Identical letters in the same column indicate values belong to the same group, Scott Knott test α = 0.05

Table A5. Cumulative precipitation in the 30-day period prior to planting and stand count seven days after emergence for the winter wheat variety Fuller planted at Waukomis, OK. Planting dates were 1 October 2010 and 27 September 2011.

| Treatment | 2009 - 2010 | | 2010 - 2011 | |
|---|---|---|---|---|
| | Rainfall† | Stand count | Rainfall | Stand count |
| | mm | plants $m^{-1}$ | mm | plants $m^{-1}$ |
| | 83 | | 53 | |
| Control | | 32[a¶] | | 22[a] |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | | 30[a] | | 21[a] |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | | 31[a] | | 21[a] |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP‡ | | 29[a] | | 22[a] |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | | 30[a] | | 22[a] |
| 2.25 Mg $ha^{-1}$ ECCE§ | | 31[a] | | 21[a] |
| 4.50 Mg $ha^{-1}$ ECCE | | 32[a] | | 25[a] |
| Significance | | | | |
| Rep | | NS | | NS |
| Treatment | | NS | | NS |
| Residual | | | | |
| CV (%) | | 10.1 | | 12.63 |

NS Non-significant

† Total rainfall in the 30-day period prior to planting date

‡ TSP, triple super phosphate applied with seed in furrow

§ ECCE, effective calcium carbonate equivalent, broadcast and incorporated

¶ Identical letters in the same column indicate no significant difference at $\alpha = 0.05$

Table A6. Effects of acidity amendment treatment on winter wheat canopy cover estimated via digital imagery measured throughout the growing seasons of 2009-10, 2010-11, and 2011-12 at Waukomis, OK.

| | | Treatment | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | 225 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 450 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 28 kg ha$^{-1}$ yr$^{-1}$ TSP | | 56 kg ha$^{-1}$ yr$^{-1}$ TSP | | 2.3 Mg ha$^{-1}$ ECCE | | 4.5 Mg ha$^{-1}$ ECCE | |
| Growing Season | GDD (Date) | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV |
| 2009-10 | 305 (11-19-09) | 6.42 | 0.85 | 6.40 | 0.47 | 6.88 | 0.67 | 8.23 | 1.39 | 9.53 | 0.72 | 5.96 | 0.88 | 5.99 | 0.68 |
| | 430 (12-14-09) | 6.84 | 1.88 | 7.12 | 1.64 | 7.41 | 2.05 | 13.38 | 2.86 | 17.98 | 2.02 | 6.73 | 1.98 | 6.44 | 1.34 |
| | 1025 (4-8-10) | 65.06 | 16.15 | 66.14 | 12.90 | 70.13 | 7.31 | 83.43 | 9.46 | 91.21 | 4.38 | 76.15 | 10.63 | 73.17 | 7.64 |
| 2010-11 | 235 (10-13-10) | 5.71 | 1.17 | 4.99 | 1.00 | 5.39 | 1.08 | 4.71 | 1.15 | 5.99 | 0.27 | 7.76 | 0.72 | 5.79 | 1.54 |
| | 510 (10-29-10) | 16.23 | 4.96 | 12.60 | 3.22 | 13.77 | 1.49 | 28.04 | 8.04 | 39.91 | 3.28 | 39.07 | 7.95 | 33.94 | 10.01 |
| | 675 (11-10-10) | 34.37 | 11.75 | 26.41 | 7.30 | 29.84 | 1.77 | 56.75 | 12.19 | 71.60 | 4.76 | 63.79 | 8.92 | 57.36 | 11.34 |
| | 822 (11-29-10) | 58.92 | 12.73 | 50.83 | 13.05 | 55.52 | 2.25 | 81.61 | 8.97 | 90.97 | 2.21 | 86.00 | 6.42 | 79.00 | 9.89 |
| | 868 (12-13-10) | 59.39 | 12.98 | 54.08 | 11.92 | 53.69 | 1.83 | 79.71 | 9.44 | 89.04 | 3.27 | 83.41 | 8.04 | 77.85 | 9.04 |
| | 962 (1-19-11) | 35.30 | 7.00 | 31.59 | 6.42 | 34.74 | 1.74 | 57.39 | 12.53 | 71.01 | 5.06 | 61.46 | 7.92 | 51.21 | 12.03 |
| | 1122 (2-22-11) | 49.51 | 7.78 | 44.69 | 6.19 | 49.95 | 5.53 | 62.98 | 11.05 | 73.36 | 4.34 | 69.47 | 6.15 | 59.98 | 6.01 |
| | 1242 (3-10-11) | 75.56 | 8.43 | 70.46 | 9.49 | 72.36 | 6.33 | 83.55 | 7.11 | 91.39 | 2.05 | 90.66 | 4.48 | 83.35 | 5.11 |
| | 1463 (3-30-11) | 72.06 | 6.63 | 69.51 | 6.31 | 73.89 | 3.66 | 79.59 | 7.20 | 83.25 | 1.37 | 83.24 | 3.72 | 78.40 | 5.43 |
| 2011-12 | 318 (10-13-11) | 2.38 | 1.49 | 1.32 | 0.38 | 1.90 | 0.45 | 1.84 | 0.65 | 1.76 | 0.50 | 1.84 | 1.00 | 2.34 | 1.29 |
| | 424 (10-20-11) | 2.99 | 1.55 | 2.27 | 0.34 | 2.63 | 0.58 | 3.82 | 1.21 | 4.54 | 0.89 | 2.60 | 0.82 | 3.38 | 1.20 |
| | 606 (11-2-11) | 22.97 | 4.07 | 21.11 | 3.49 | 23.06 | 1.17 | 30.53 | 3.92 | 36.66 | 3.03 | 22.79 | 4.57 | 28.19 | 2.85 |
| | 680 (11-10-11) | 39.28 | 5.42 | 36.28 | 5.86 | 37.70 | 2.14 | 46.03 | 5.72 | 56.27 | 3.83 | 39.13 | 5.22 | 48.15 | 4.58 |
| | 786 (11-22-11) | 61.16 | 6.64 | 56.19 | 5.74 | 59.04 | 1.43 | 63.39 | 4.47 | 74.01 | 4.07 | 53.99 | 9.10 | 63.60 | 6.34 |
| | 902 (12-15-11) | 74.79 | 4.75 | 68.44 | 5.24 | 72.83 | 1.16 | 77.49 | 5.85 | 86.33 | 3.62 | 67.56 | 10.30 | 73.47 | 8.05 |
| | 1076 (1-19-12) | 78.63 | 3.09 | 71.29 | 7.41 | 73.88 | 4.29 | 77.54 | 4.92 | 88.85 | 3.63 | 63.39 | 11.19 | 71.91 | 9.19 |
| | 1372 (3-6-12) | 90.75 | 1.92 | 87.75 | 2.17 | 87.00 | 1.87 | 93.25 | 1.92 | 96.75 | 0.43 | 82.50 | 4.09 | 83.75 | 5.72 |
| | 1726 (3-29-12) | 98.72 | 0.11 | 98.43 | 0.68 | 98.16 | 0.56 | 98.59 | 0.49 | 98.96 | 0.14 | 97.28 | 1.71 | 97.79 | 1.16 |

Table A7. Effects of acidity amendment treatment on winter wheat NDVI estimated via GreenSeeker sensor measured throughout the growing seasons of 2009-10, 2010-11, and 2011-12 at Waukomis, OK.

| | | Treatment | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | 225 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 450 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 28 kg ha$^{-1}$ yr$^{-1}$ TSP | | 56 kg ha$^{-1}$ yr$^{-1}$ TSP | | 2.3 Mg ha$^{-1}$ ECCE | | 4.5 Mg ha$^{-1}$ ECCE | |
| Growing Season | GDD (Date) | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV |
| 2009-10 | 305 (11-19-09) | 0.19 | 0.01 | 0.19 | 0.00 | 0.19 | 0.00 | 0.19 | 0.01 | 0.20 | 0.01 | 0.18 | 0.00 | 0.18 | 0.00 |
| | 430 (12-14-09) | 0.22 | 0.01 | 0.22 | 0.01 | 0.22 | 0.01 | 0.24 | 0.01 | 0.26 | 0.01 | 0.21 | 0.01 | 0.21 | 0.01 |
| | 1025 (4-8-10) | 0.59 | 0.12 | 0.61 | 0.10 | 0.61 | 0.05 | 0.69 | 0.06 | 0.75 | 0.07 | 0.60 | 0.10 | 0.60 | 0.06 |
| 2010-11 | 235 (10-13-10) | 0.18 | 0.01 | 0.18 | 0.00 | 0.18 | 0.00 | 0.18 | 0.01 | 0.18 | 0.00 | 0.18 | 0.01 | 0.18 | 0.01 |
| | 510 (10-29-10) | 0.23 | 0.02 | 0.22 | 0.02 | 0.24 | 0.02 | 0.29 | 0.01 | 0.34 | 0.02 | 0.31 | 0.03 | 0.32 | 0.03 |
| | 675 (11-10-10) | 0.31 | 0.04 | 0.31 | 0.03 | 0.34 | 0.03 | 0.47 | 0.01 | 0.56 | 0.02 | 0.49 | 0.06 | 0.50 | 0.04 |
| | 822 (11-29-10) | 0.38 | 0.06 | 0.37 | 0.04 | 0.40 | 0.03 | 0.54 | 0.03 | 0.65 | 0.03 | 0.56 | 0.06 | 0.58 | 0.06 |
| | 868 (12-13-10) | 0.46 | 0.07 | 0.46 | 0.06 | 0.49 | 0.05 | 0.65 | 0.02 | 0.74 | 0.03 | 0.65 | 0.06 | 0.66 | 0.04 |
| | 962 (1-19-11) | 0.42 | 0.06 | 0.42 | 0.06 | 0.45 | 0.05 | 0.53 | 0.05 | 0.60 | 0.03 | 0.56 | 0.06 | 0.54 | 0.05 |
| | 1122 (2-22-11) | 0.64 | 0.04 | 0.63 | 0.05 | 0.67 | 0.04 | 0.72 | 0.05 | 0.76 | 0.01 | 0.74 | 0.03 | 0.73 | 0.03 |
| | 1242 (3-10-11) | 0.61 | 0.04 | 0.61 | 0.04 | 0.64 | 0.04 | 0.69 | 0.05 | 0.71 | 0.01 | 0.70 | 0.04 | 0.68 | 0.04 |
| | 1463 (3-30-11) | 0.21 | 0.01 | 0.21 | 0.00 | 0.21 | 0.01 | 0.21 | 0.00 | 0.21 | 0.01 | 0.21 | 0.00 | 0.21 | 0.01 |
| 2011-12 | 318 (10-13-11) | 0.17 | 0.00 | 0.17 | 0.00 | 0.17 | 0.01 | 0.17 | 0.01 | 0.18 | 0.00 | 0.17 | 0.00 | 0.17 | 0.00 |
| | 424 (10-20-11) | 0.27 | 0.01 | 0.26 | 0.01 | 0.25 | 0.01 | 0.28 | 0.01 | 0.34 | 0.02 | 0.27 | 0.02 | 0.28 | 0.01 |
| | 606 (11-2-11) | 0.43 | 0.01 | 0.41 | 0.01 | 0.41 | 0.03 | 0.45 | 0.02 | 0.53 | 0.02 | 0.44 | 0.02 | 0.44 | 0.02 |
| | 680 (11-10-11) | 0.61 | 0.03 | 0.59 | 0.02 | 0.58 | 0.02 | 0.64 | 0.01 | 0.71 | 0.02 | 0.61 | 0.02 | 0.62 | 0.03 |
| | 786 (11-22-11) | 0.64 | 0.02 | 0.62 | 0.01 | 0.61 | 0.02 | 0.67 | 0.01 | 0.74 | 0.02 | 0.62 | 0.02 | 0.62 | 0.02 |
| | 902 (12-15-11) | 0.68 | 0.02 | 0.67 | 0.02 | 0.65 | 0.01 | 0.73 | 0.01 | 0.79 | 0.02 | 0.64 | 0.02 | 0.64 | 0.04 |
| | 1076 (1-19-12) | 0.77 | 0.02 | 0.75 | 0.01 | 0.74 | 0.04 | 0.79 | 0.02 | 0.83 | 0.02 | 0.73 | 0.04 | 0.72 | 0.02 |
| | 1372 (3-6-12) | 0.77 | 0.03 | 0.74 | 0.03 | 0.71 | 0.02 | 0.78 | 0.02 | 0.82 | 0.03 | 0.67 | 0.02 | 0.65 | 0.04 |
| | 1726 (3-29-12) | 0.82 | 0.01 | 0.82 | 0.01 | 0.79 | 0.02 | 0.82 | 0.02 | 0.83 | 0.01 | 0.79 | 0.04 | 0.81 | 0.01 |

Table A8. Effects of acidity amendment treatment on winter wheat NDVI CV estimated via GreenSeeker sensor measured throughout the growing seasons of 2009-10, 2010-11, and 2011-12 at Waukomis, OK.

| Growing Season | GDD (Date) | Treatment | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control | | 225 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 450 kg ha$^{-1}$ yr$^{-1}$ Pell lime | | 28 kg ha$^{-1}$ yr$^{-1}$ TSP | | 56 kg ha$^{-1}$ yr$^{-1}$ TSP | | 2.3 Mg ha$^{-1}$ ECCE | | 4.5 Mg ha$^{-1}$ ECCE | |
| | | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV |
| 2009-10 | 305 (11-19-09) | 3.85 | 0.58 | 3.83 | 0.55 | 4.37 | 0.25 | 4.77 | 0.55 | 5.08 | 1.75 | 4.25 | 0.79 | 4.49 | 0.66 |
| | 430 (12-14-09) | 7.26 | 1.11 | 6.36 | 1.23 | 6.32 | 0.74 | 7.73 | 1.40 | 8.63 | 2.34 | 7.61 | 2.77 | 6.61 | 1.84 |
| | 1025 (4-8-10) | 17.64 | 3.70 | 16.93 | 5.47 | 17.65 | 1.12 | 12.34 | 1.46 | 12.66 | 7.76 | 19.37 | 2.09 | 16.42 | 3.42 |
| 2010-11 | 235 (10-13-10) | 4.93 | 0.65 | 4.66 | 0.74 | 4.48 | 0.63 | 4.18 | 0.59 | 4.16 | 1.25 | 4.63 | 0.87 | 4.65 | 1.53 |
| | 510 (10-29-10) | 12.27 | 5.62 | 8.51 | 4.86 | 9.91 | 4.67 | 13.88 | 3.23 | 13.89 | 1.74 | 14.88 | 2.18 | 14.34 | 3.43 |
| | 675 (11-10-10) | 20.85 | 7.44 | 17.51 | 3.31 | 13.98 | 3.45 | 15.47 | 2.08 | 12.42 | 1.26 | 16.23 | 1.40 | 14.11 | 4.24 |
| | 822 (11-29-10) | 22.30 | 5.95 | 17.20 | 1.88 | 15.49 | 4.45 | 15.19 | 2.57 | 11.51 | 1.33 | 16.36 | 1.58 | 15.81 | 4.11 |
| | 868 (12-13-10) | 20.34 | 6.17 | 16.35 | 3.85 | 13.37 | 2.39 | 12.03 | 2.85 | 8.34 | 1.46 | 12.46 | 1.32 | 12.08 | 3.03 |
| | 962 (1-19-11) | 20.71 | 5.17 | 18.00 | 2.90 | 16.14 | 4.45 | 14.81 | 3.87 | 11.90 | 1.74 | 15.06 | 2.35 | 13.83 | 3.75 |
| | 1122 (2-22-11) | 15.19 | 4.32 | 10.78 | 1.93 | 10.04 | 2.76 | 6.42 | 2.76 | 4.25 | 0.67 | 6.15 | 0.97 | 5.33 | 1.10 |
| | 1242 (3-10-11) | 16.98 | 3.98 | 13.67 | 2.93 | 12.21 | 1.98 | 9.12 | 3.22 | 6.02 | 0.43 | 9.06 | 1.87 | 8.25 | 2.15 |
| | 1463 (3-30-11) | 7.15 | 1.16 | 7.60 | 1.02 | 7.26 | 0.52 | 7.01 | 1.21 | 6.33 | 0.96 | 7.63 | 0.86 | 8.48 | 1.70 |
| 2011-12 | 318 (10-13-11) | 4.10 | 0.72 | 4.57 | 0.61 | 3.44 | 0.61 | 5.00 | 1.31 | 5.85 | 0.81 | 4.56 | 1.04 | 4.79 | 0.55 |
| | 424 (10-20-11) | 13.12 | 2.10 | 14.14 | 1.74 | 12.31 | 3.01 | 15.41 | 2.14 | 15.60 | 3.09 | 14.08 | 2.47 | 13.57 | 1.67 |
| | 606 (11-2-11) | 14.11 | 1.64 | 15.18 | 4.02 | 13.04 | 0.51 | 15.23 | 2.06 | 12.41 | 3.43 | 15.24 | 3.22 | 13.39 | 0.64 |
| | 680 (11-10-11) | 11.79 | 2.61 | 12.16 | 3.25 | 11.62 | 1.12 | 10.03 | 2.95 | 8.23 | 1.46 | 12.39 | 3.45 | 10.63 | 1.22 |
| | 786 (11-22-11) | 12.36 | 1.15 | 12.92 | 2.84 | 11.81 | 1.81 | 11.18 | 2.92 | 8.66 | 1.96 | 13.57 | 2.59 | 11.71 | 1.13 |
| | 902 (12-15-11) | 10.35 | 2.32 | 11.48 | 3.06 | 10.61 | 1.31 | 9.95 | 2.19 | 7.47 | 1.96 | 13.13 | 2.32 | 11.32 | 1.28 |
| | 1076 (1-19-12) | 6.12 | 1.72 | 7.34 | 1.21 | 7.73 | 2.84 | 5.92 | 2.25 | 3.87 | 1.94 | 8.35 | 1.95 | 8.64 | 1.06 |
| | 1372 (3-6-12) | 8.08 | 0.36 | 9.51 | 1.95 | 11.82 | 1.58 | 7.01 | 1.77 | 7.22 | 2.97 | 13.50 | 1.46 | 12.55 | 2.28 |
| | 1726 (3-29-12) | 2.07 | 0.81 | 2.31 | 0.40 | 3.88 | 1.60 | 2.61 | 0.93 | 2.16 | 0.79 | 3.53 | 1.36 | 3.37 | 0.64 |

Table A9. Winter wheat enterprise budget with variable cost estimates for each year of the study. Prices are based on the NASS March report times the index for each specific month. Total variable costs are the same for every treatment.

| | | 2009-2010 | | | 2010-2011 | | | 2011-2012 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Treatment | | | Treatment | | | Treatment | |
| Item | Unit | Price | Quantity | Value | Price | Quantity | Value | Price | Quantity | Value |
| **Production** | | | | | | | | | | |
| *Wheat* | Bu | $ 4.09 | Yield | Yied*4.09 | $ 7.42 | Yield | Yied*7.42 | $ 6.15 | Yield | Yied*6.15 |
| Gross Income | acre | | | | | | | | | |
| **"Cash" Costs** | | | | | | | | | | |
| *Two Summer Tillages* | Bu. | $ 40.00 | 1.00 | 40.00 | 40.0 | 1.0 | 40.00 | 40.0 | 1.0 | 40.00 |
| *Wheat Seed* | Bu. | $ 13.00 | 1.00 | 13.00 | 11.0 | 1.0 | 11.00 | 12.0 | 1.0 | 12.00 |
| *Planting operation* | acre | $ 12.00 | 1.00 | 12.00 | 12.0 | 1.0 | 12.00 | 12.0 | 1.0 | 12.00 |
| *Anhydrous Ammonia )* | Ton | $ 552.89 | 0.03 | 17.56 | 730.0 | 0.03 | 23.18 | 817.9 | 0.03 | 25.98 |
| *Fertilizer Application* | acre | $ 9.00 | 1.00 | 9.00 | 9.0 | 1.0 | 9.00 | 9.0 | 1.0 | 9.00 |
| *Liquid N (28-0-0)* | Ton | $ 275.35 | 0.01 | 2.75 | 383.2 | 0.01 | 3.83 | 405.3 | 0.05 | 18.39 |
| *Fertilizer Application* | acre | $ 5.00 | 0.50 | 2.50 | 5.0 | 0.5 | 2.50 | 5.0 | 0.5 | 2.50 |
| *Urea (46-0-0)* | Ton | $ 411.29 | 0.05 | 20.53 | 622.7 | 0.1 | 45.21 | 580.2 | 0.05 | 28.96 |
| *Fertilizer Application* | acre | $ 4.00 | 1 | 4.00 | 4.0 | 1 | 4.00 | 4.0 | 1.0 | 4.00 |
| *Herbicide (Olympus Flex)* | gal | $ 498.41 | 0.00 | 0.00 | 489.2 | 0.03 | 13.38 | 495.7 | 0.00 | 0.00 |
| *Herbicide (MCPA)* | gal | $ 21.47 | 0.00 | 0.00 | 22.2 | 0 | 0.00 | 21.1 | 0.13 | 2.64 |
| *Herbicide Application* | acre | $ 5.00 | 0.5 | 2.50 | 5.0 | 0.5 | 2.50 | 5.0 | 0.5 | 2.50 |
| *Insecticide (Lorsban)* | gal | $ 42.00 | 0.09 | 3.94 | 40.7 | 0.09 | 3.81 | 0.0 | 0.0 | 0.00 |
| *Insecticide Application* | acre | $ 5.00 | 1 | 5.00 | 5.0 | 1.0 | 5.00 | 5.0 | 1.0 | 5.00 |
| *Fungicide (Twinline)* | gal | $ 254.16 | 0.07 | 17.87 | 249.4 | 0.07 | 17.54 | 253.3 | 0.07 | 17.81 |
| *Fungicide Application* | acre | $ 5.00 | 1 | 5.00 | 5.0 | 1.0 | 5.00 | 5.0 | 1.0 | 5.00 |
| *Wheat Crop Insurance* | acre | $ 7.00 | 1 | 7.00 | $ 7.00 | 1 | 7.00 | $ 7.00 | 1 | 7.00 |
| *Fuel* | gal | $ 2.54 | 4.92 | 12.50 | $ 3.53 | 4.92 | 17.38 | $ 3.71 | 4.92 | 18.27 |
| *Annual Operating Capital* | $ | | 78.33 | 5.71 | | 120.81 | 8.56 | | 91.18 | 6.28 |
| **Custom Harvest & Haul** | | | | | | | | | | |
| *Base Charge* | acre | $ 16.97 | 1 | 17.0 | $ 17.47 | 1 | 17.5 | $ 18.00 | 1 | 18.0 |
| *Excess for > 20 bu/a* | bu | $ 0.17 | 21.3 | (Yield-20)*0.17 | $ 0.17 | 3.06 | (Yield-20)*0.17 | $ 0.18 | 45.10 | (Yield-20)*0.18 |
| *Hauling* | bu | $ 0.17 | 41.3 | Yield*0.17 | $ 0.17 | 23.06 | Yield*0.17 | $ 0.18 | 65.10 | Yield*0.18 |
| *Total Variable costs* | | | | *208.46* | | | *252.92* | | | *255.16* |

Table A10. Winter wheat net return as affected by liming treatment with lime costs fully assessed in the year of application or amortized over a 5 year period for the growing seasons 2009-2010, 2010-201, and 2011-2012. Total variable costs are the same for every treatment.

| | | | | Broadcast Aglime | | | |
|---|---|---|---|---|---|---|---|
| Item | Year | Unit | Price | Quantity | Value | Quantity | Value |
| Production | | | | bu/ac | 2000 lb ac$^{-1}$ | bu/ac | 4000 lb ac$^{-1}$ |
| *Wheat* | *2009-2010* | Bu | $ 4.09 | 52 | 212 | 49 | 201 |
| Gross Income | | acre | | | 212 | | 201 |
| Total Costs | | | | | | | |
| *Lime costs at 1st year* | | acre | | | 247 | | 256 |
| *Lime costs amortized (5-yr)* | | acre | | | 221 | | 207 |
| Return | | | | | | | |
| *Lime costs at 1st year* | | acre | | | -36 | | -55 |
| *Lime costs amortized (5-yr)* | | acre | | | -9 | | -7 |
| *Wheat* | *2010-2011* | Bu | $ 7.42 | 23 | 171 | 24 | 181 |
| Gross Income | | acre | | | 171 | | 181 |
| Total Costs | | | | | | | |
| *Lime costs at 1st year* | | acre | | | 253 | | 253 |
| *Lime costs amortized (5-yr)* | | acre | | | 262 | | 269 |
| Return | | | | | | | |
| *Lime costs at 1st year* | | acre | | | -82 | | -72 |
| *Lime costs amortized (5-yr)* | | acre | | | -90 | | -88 |
| *Wheat* | *2011-2012* | Bu | $ 6.15 | 65 | 400 | 66 | 408 |
| Gross Income | | acre | | | 400 | | 408 |
| Total Costs | | | | | | | |
| *Lime costs at 1st year* | | acre | | | 255 | | 256 |
| *Lime costs amortized (5-yr)* | | acre | | | 264 | | 271 |
| Return | | | | | | | |
| *Lime costs at 1st year* | | acre | | | 145 | | 153 |
| *Lime costs amortized (5-yr)* | | acre | | | 137 | | 137 |

Table A11. Monthly reference evapotranspiration and total precipitation for the winter wheat growing seasons of 2009-2009, 2009-2010, and 2010-2011 at Altus, OK.

| Month | 2008-2009 | | 2009-2010 | | 2010-2011 | | |
|---|---|---|---|---|---|---|---|
| | $ET_0$† | Rainfall | $ET_0$ | Rainfall | $ET_0$ | Rainfall | 30-yr Normal‡ |
| | | | | mm | | | |
| October | 108 | 93 | 70 | 92 | 117 | 50 | 69 |
| November | 83 | 1 | 65 | 7 | 83 | 23 | 38 |
| December | 72 | 1 | 41 | 42 | 63 | 0 | 31 |
| January | 81 | 9 | 39 | 79 | 57 | 1 | 24 |
| February | 104 | 8 | 40 | 26 | 77 | 14 | 30 |
| March | 137 | 50 | 110 | 23 | 138 | 1 | 45 |
| April | 162 | 144 | 151 | 72 | 224 | 4 | 62 |
| May | 148 | 71 | 182 | 79 | 248 | 18 | 122 |
| GS Total | 893 | 376 | 697 | 420 | 1007 | 110 | 421 |

† Reference evapotranspiration estimated by the Penman-Monteith methodology modified by FAO (Food and Agriculture Organization, Rome, Italy)

‡ 30 year normal precipitation

Table A12. Normalized difference vegetative index (NDVI), percent canopy cover (CC), plant stand, wheat grain test weight and percent protein content of the winter wheat variety Fuller as affected by acidity amendment treatment for the growing seasons 2008-09, 2009-10, and 2010-11 at Altus, OK.

| | 2008-2009 | | | 2009-2010 | | | | 2010-2011 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | NDVI† | CC‡ | Test weight | NDVI | CC | Test weight | Protein | Stand | Test weight | Protein |
| | | % | kg $hl^{-1}$ | | % | kg $hl^{-1}$ | % | pl $m^{-1}$ | kg $hl^{-1}$ | % |
| Control | 0.21a†† | 11.6ab | 75.9a | 0.29a | 27.5c | 74a | 15.5a | 33b | 75.2a | 13.8a |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 0.23a | 12.4ab | 75.3ab | 0.33a | 36.3bc | 73.9a | 15.7a | 36ab | 75.1a | 13.8a |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 0.24a | 11.0b | 74.0b | 0.34a | 37.1bc | 73.6a | 15.4a | 34b | 75.9a | 13.3a |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP§ | 0.24a | 11.4ab | 75.0ab | 0.33a | 39.4ab | 74.3a | 15.5a | 36ab | 75.9a | 13.5a |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 0.24a | 14.2a | 75.5ab | 0.35a | 43.5ab | 74.1a | 15.7a | 37ab | 75.8a | 13.7a |
| 2.25 Mg $ha^{-1}$ ECCE¶ | 0.24a | 11.4ab | 74.5ab | 0.36a | 38.9ab | 75a | 15.8a | 36ab | 75.9a | 13.7a |
| 4.50 Mg $ha^{-1}$ ECCE | 0.23a | 11.5ab | 75.5ab | 0.38a | 49.2a | 73.5a | 16.2a | 38a | 75.6a | 14.1a |
| Significance | | | | | | | | | | |
| Rep | * | ** | ** | * | ** | ns | ns | ns | ns | ns |
| Treatment | ns | ns | ns | ns | ** | ns | ns | ns | ns | ns |
| Residual | | | | | | | | | | |
| CV (%) | 8.83 | 14.72 | 1.37 | 16.36 | 17.18 | 0.89 | 3.35 | 6.78 | 0.94 | 3.67 |

† Normalized difference vegetative index (NDVI) measured with Greenseeker Sensor
‡ Canopy cover measured via digital imagery analysis
§ TSP, triple super phosphate applied with seed in furrow
¶ ECCE, effective calcium carbonate equivalent, broadcast and incorporated
†† Identical letters in the same column indicate no significant difference at $\alpha = 0.05$

Table A13. Normalized difference vegetative index (NDVI) estimated via Greenseeker Sensor and NDVI standard deviation of the repetitions (STDEV) throughout the 2010-2011 growing season for the winter wheat variety Fuller as affected by acidity amendment treatment at Altus, OK.

| | 11/11/2010 | | 12/2/2010 | | 12/15/2010 | | 2/15/2011 | | 3/12/2011 | | 4/2/2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV | NDVI | STDEV |
| Control | 0.19 | 0.00 | 0.30 | 0.01 | 0.32 | 0.01 | 0.30 | 0.04 | 0.46 | 0.04 | 0.47 | 0.04 |
| 225 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 0.20 | 0.01 | 0.31 | 0.01 | 0.32 | 0.02 | 0.29 | 0.05 | 0.42 | 0.08 | 0.42 | 0.06 |
| 450 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 0.20 | 0.01 | 0.33 | 0.03 | 0.36 | 0.04 | 0.31 | 0.05 | 0.39 | 0.09 | 0.37 | 0.09 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP† | 0.20 | 0.01 | 0.35 | 0.04 | 0.37 | 0.04 | 0.34 | 0.03 | 0.42 | 0.07 | 0.40 | 0.06 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 0.20 | 0.01 | 0.35 | 0.02 | 0.39 | 0.02 | 0.39 | 0.04 | 0.48 | 0.05 | 0.44 | 0.04 |
| 2.25 Mg $ha^{-1}$ ECCE‡ | 0.20 | 0.01 | 0.37 | 0.02 | 0.41 | 0.02 | 0.35 | 0.02 | 0.44 | 0.05 | 0.41 | 0.04 |
| 4.50 Mg $ha^{-1}$ ECCE | 0.22 | 0.02 | 0.38 | 0.03 | 0.41 | 0.05 | 0.39 | 0.06 | 0.52 | 0.06 | 0.48 | 0.06 |

† TSP, triple super phosphate applied with seed in furrow

‡ ECCE, effective calcium carbonate equivalent

Table A14. Percent canopy coverage (CC) estimated via digital imagery and standard deviation of the repetitions (STDEV) throughout the 2010-2011 growing season for the winter wheat variety Fuller as affected by acidity amendment treatment at Altus, OK.

| | 11/11/2010 | | 12/2/2010 | | 12/15/2010 | | 2/15/2011 | | 3/12/2011 | | 4/2/2011 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV | CC | STDEV |
| Control | 4.9 | 2.1 | 18.3 | 1.7 | 17.3 | 2.6 | 9.8 | 2.5 | 38.1 | 5.6 | 36.3 | 2.6 |
| 224 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 5.1 | 1.5 | 19.9 | 2.4 | 17.3 | 2.4 | 7.7 | 3.2 | 26.6 | 11.4 | 29.8 | 10.3 |
| 448 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 9.9 | 7.6 | 22.2 | 2.9 | 22.0 | 3.5 | 8.6 | 4.7 | 22.1 | 12.7 | 26.1 | 8.5 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP† | 5.0 | 1.0 | 25.2 | 5.5 | 23.2 | 5.0 | 9.5 | 5.9 | 27.1 | 15.6 | 33.8 | 7.2 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 5.9 | 1.9 | 25.5 | 4.4 | 29.2 | 3.9 | 17.0 | 5.3 | 38.5 | 9.4 | 40.3 | 5.8 |
| 2.25 Mg $ha^{-1}$ ECCE‡ | 4.8 | 0.9 | 28.7 | 3.1 | 30.5 | 3.0 | 13.9 | 4.7 | 34.0 | 10.9 | 34.8 | 4.9 |
| 4.50 Mg $ha^{-1}$ ECCE | 6.1 | 1.8 | 34.2 | 14.0 | 35.2 | 10.2 | 17.0 | 3.4 | 49.9 | 7.5 | 39.8 | 3.8 |

† TSP, triple super phosphate applied with seed in furrow

‡ ECCE, effective calcium carbonate equivalent

Table A15. Normalized difference vegetative index coefficient of variation (NDVI CV) estimated via Greenseeker Sensor and NDVI standard deviation of the repetitions (STDEV) throughout the 2010-2011 growing season for the winter wheat variety Fuller as affected by acidity amendment treatment at Altus, OK.

| | 11/11/2011 | | 12/15/2010 | | 2/15/2011 | | 3/12/2011 | | 4/2/2011 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV | NDVI CV | STDEV |
| | % | | % | | % | | % | | % | |
| Control | 6.1 | 1.3 | 10.4 | 2.4 | 14.8 | 3.4 | 14.9 | 4.7 | 16.2 | 5.3 |
| 224 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 6.0 | 1.3 | 9.0 | 0.7 | 10.3 | 2.3 | 12.4 | 1.3 | 16.5 | 3.8 |
| 448 kg $ha^{-1}$ $yr^{-1}$ Pell Lime | 6.5 | 0.7 | 9.4 | 1.9 | 8.7 | 1.2 | 13.0 | 3.7 | 14.4 | 4.1 |
| 28 kg $ha^{-1}$ $yr^{-1}$ TSP† | 5.9 | 1.2 | 8.6 | 2.7 | 9.9 | 0.8 | 11.0 | 2.0 | 13.5 | 1.9 |
| 56 kg $ha^{-1}$ $yr^{-1}$ TSP | 7.3 | 2.6 | 8.4 | 2.1 | 8.8 | 1.7 | 9.2 | 2.3 | 10.6 | 1.0 |
| 2.25 Mg $ha^{-1}$ ECCE‡ | 8.7 | 2.8 | 8.8 | 2.4 | 12.0 | 3.3 | 12.1 | 2.3 | 13.9 | 1.8 |
| 4.50 Mg $ha^{-1}$ ECCE | 10.7 | 7.0 | 11.7 | 3.7 | 11.7 | 2.4 | 10.0 | 2.4 | 12.3 | 1.8 |

† TSP, triple super phosphate applied with seed in furrow

‡ ECCE, effective calcium carbonate equivalent

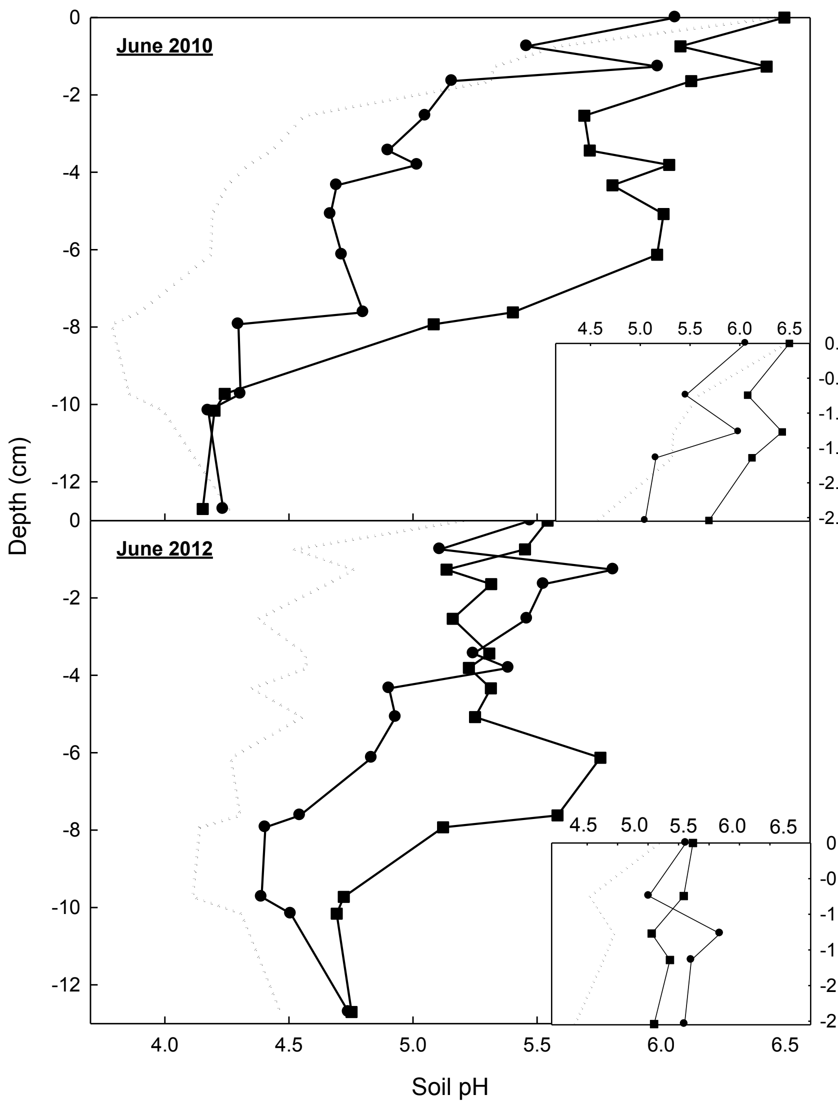


Figure A1. pH distribution across the profile depth influenced by amendment treatment measured in June 2011 and June 2012 in a Grant Silt Loam at Waukomis, OK. The graph in the bottom right details the upper part of the profile, depth at which the pelletized lime was applied. Values for each depth are an average of no more than 3 values within 1.27 cm from the main axis, averaged across 4 repetitions. Dotted line, control; black circles, 448 kg $ha^{-1}$ $yr^{-1}$ in furrow pelletized lime; black squares, 4.50 Mg $ha^{-1}$ ECCE broadcast incorporated.

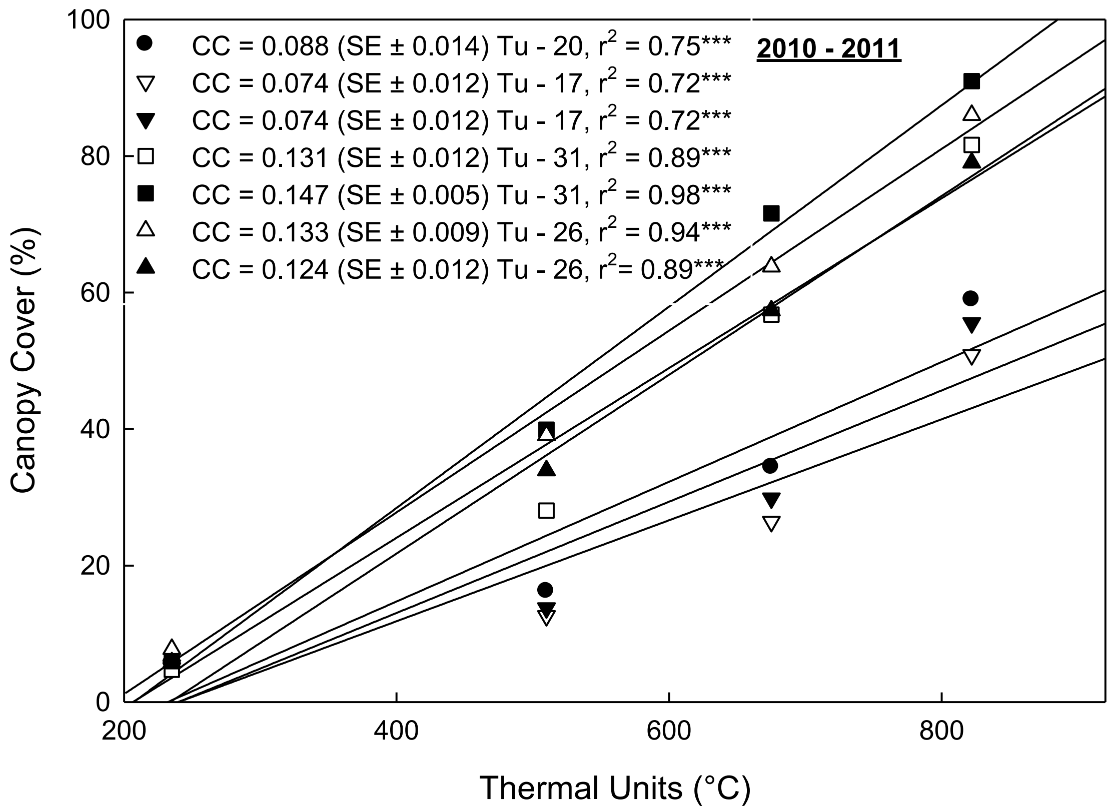


Figure A2. Relationship between canopy coverage and thermal units prior to winter dormancy as affected by acidity amendment strategy during the 2010 – 2011 winter wheat growing season at Waukomis, OK. Black circles, control; white triangles point down, 224 kg ha$^{-1}$ yr$^{-1}$ in furrow pelletized lime; black triangles pointing down, 448 kg ha$^{-1}$ yr$^{-1}$ in furrow pelletized lime; white squares, 28 kg ha$^{-1}$ yr$^{-1}$ TSP; black squares, 56 kg ha$^{-1}$ yr$^{-1}$ TSP; white triangles pointing up, 2.25 Mg ha$^{-1}$ ECCE broadcast incorporated; black triangles pointing up, 4.50 Mg ha$^{-1}$ ECCE broadcast incorporated. SE, standard error.

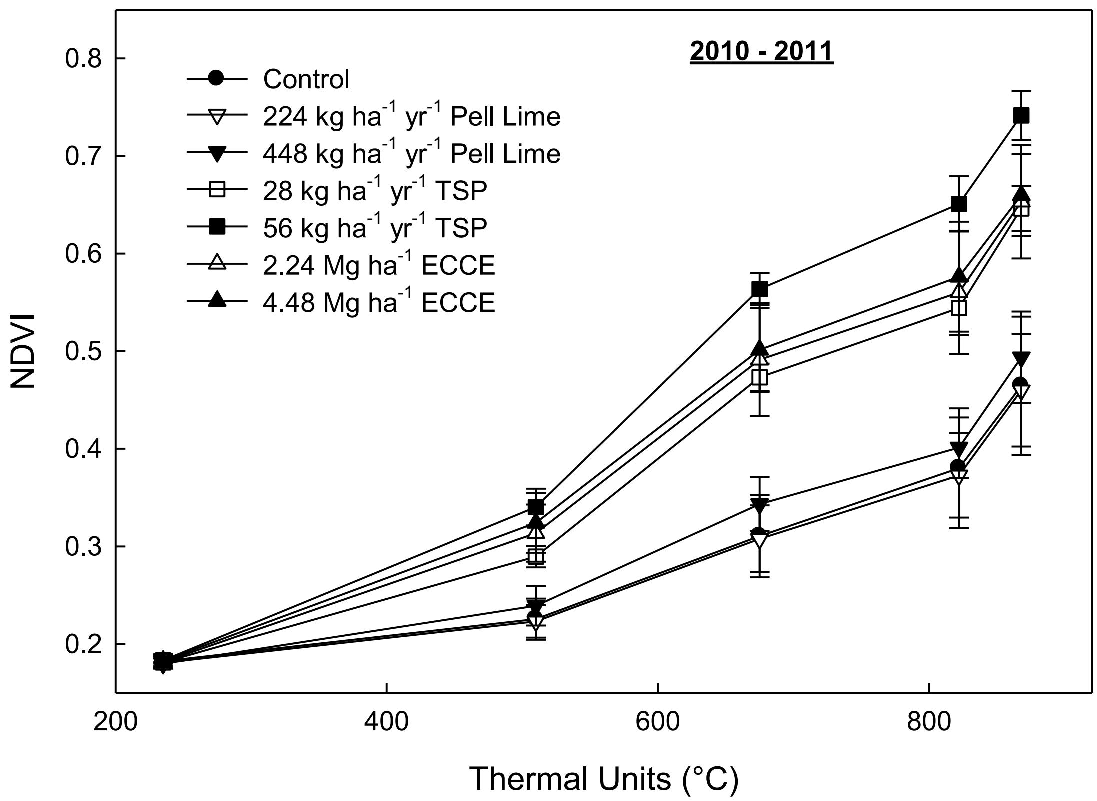


Figure A3. Mean normalized difference vegetative index (NDVI) evolution obtained via GreenSeeker sensor as a function of thermal units and influenced by acidity amendment strategy during the 2010 – 2011 winter wheat growing season at Waukomis, OK. Standard deviation indicated as error bars.

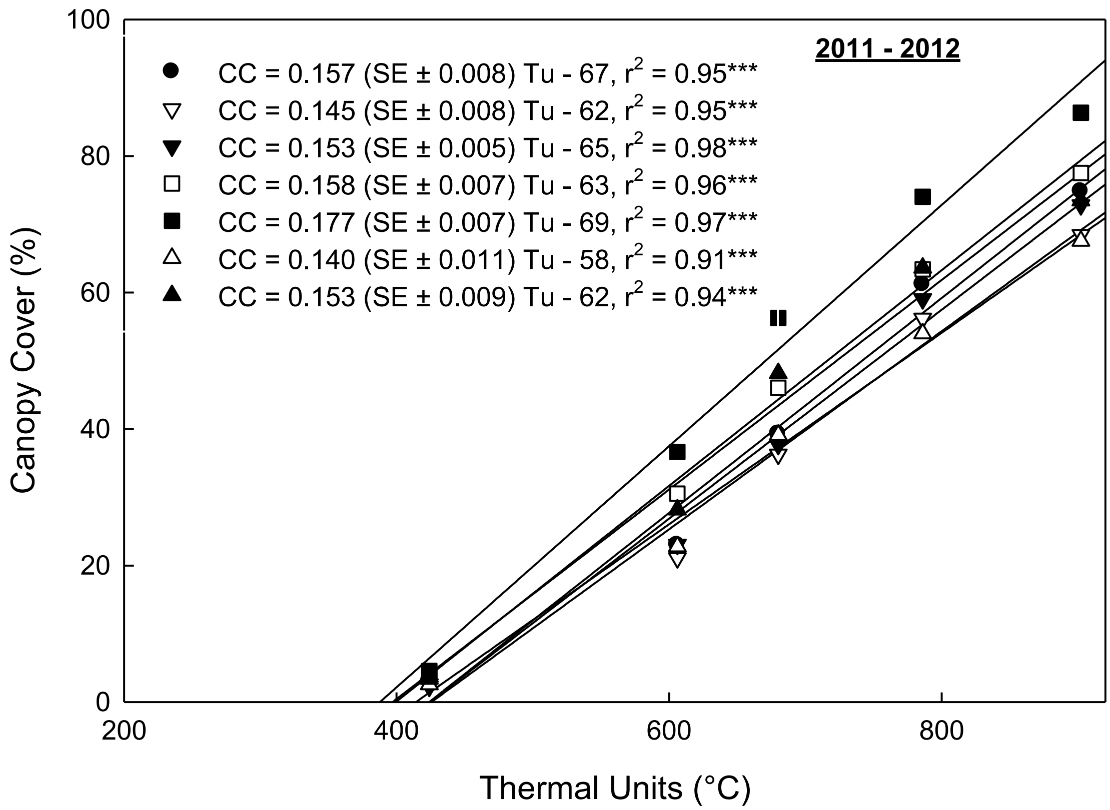


Figure A4. Relationship between canopy coverage and thermal units prior to winter dormancy as affected by acidity amendment strategy during the 2011 – 2012 winter wheat growing season at Waukomis, OK. Black circles, control; white triangles point down, 224 kg $ha^{-1}$ $yr^{-1}$ in furrow pelletized lime; black triangles pointing down, 448 kg $ha^{-1}$ $yr^{-1}$ in furrow pelletized lime; white squares, 28 kg $ha^{-1}$ $yr^{-1}$ TSP; black squares, 56 kg $ha^{-1}$ $yr^{-1}$ TSP; white triangles pointing up, 2.25 Mg $ha^{-1}$ ECCE broadcast incorporated; black triangles pointing up, 4.50 Mg $ha^{-1}$ ECCE broadcast incorporated. SE, standard error.

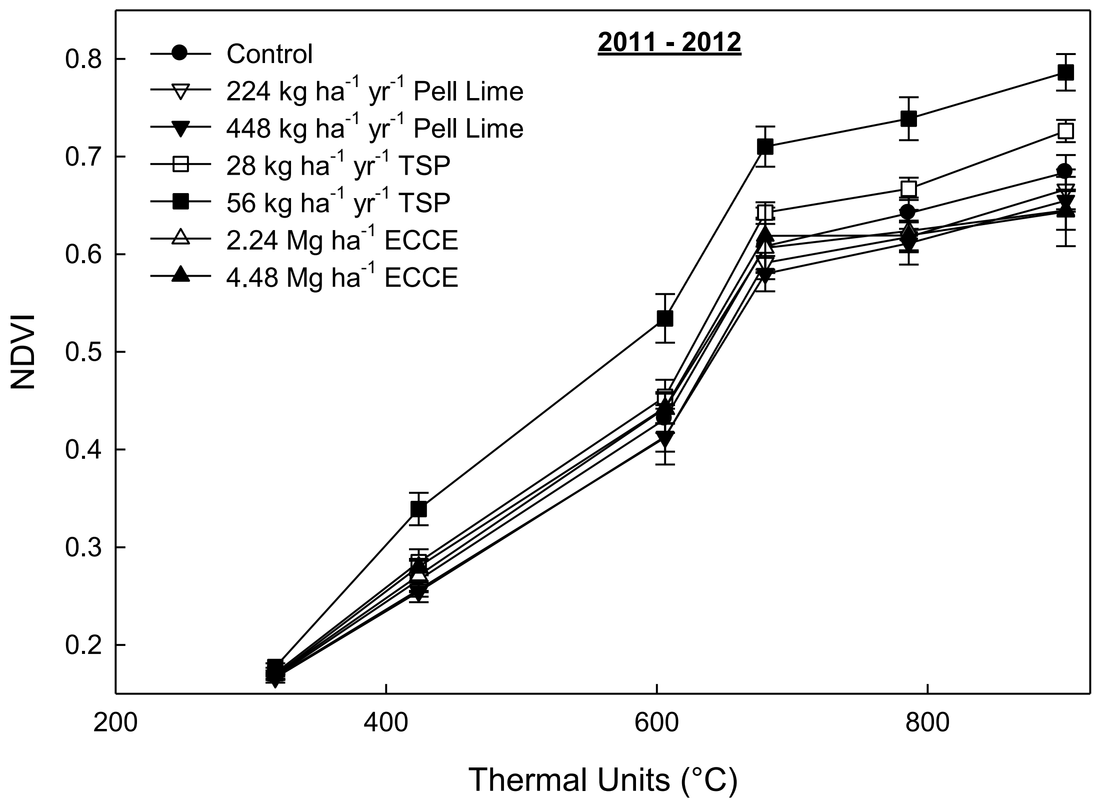


Figure A5. Mean normalized difference vegetative index (NDVI) evolution obtained via GreenSeeker sensor as a function of thermal units and influenced by acidity amendment strategy during the 2011 – 2012 winter wheat growing season at Waukomis, OK. Standard deviation indicated as error bars.

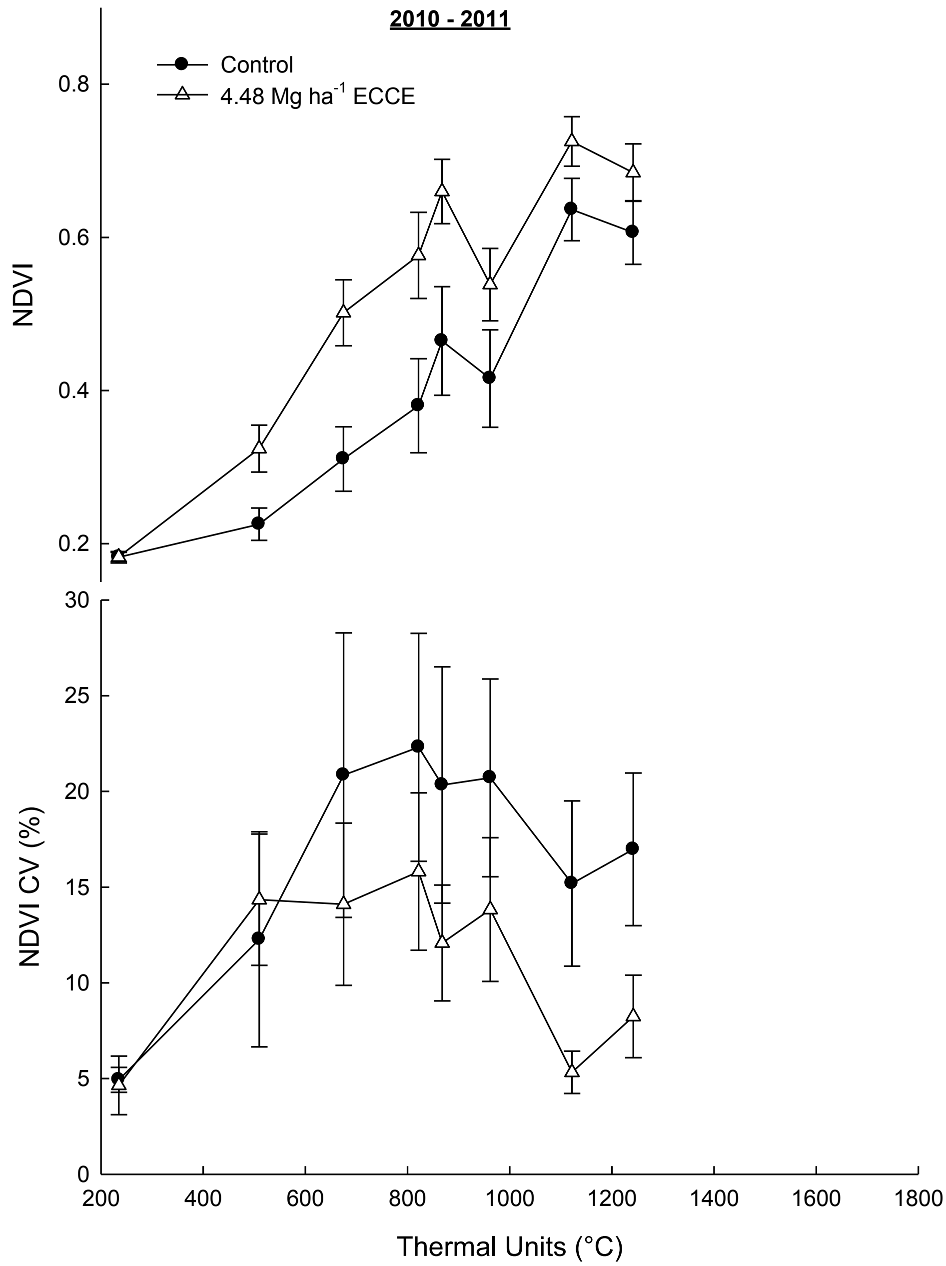


Figure A6. Mean normalized difference vegetative index (NDVI) and coefficient of variation (NDVI CV) from NDVI readings obtained via GreenSeeker sensor by thermal units as a function of treatments with and without lime application in an acid Grant Silt Loam during winter wheat growth stages Feekes 1 to Feekes 5, Waukomis, OK. Vertical bars represents standard deviation.

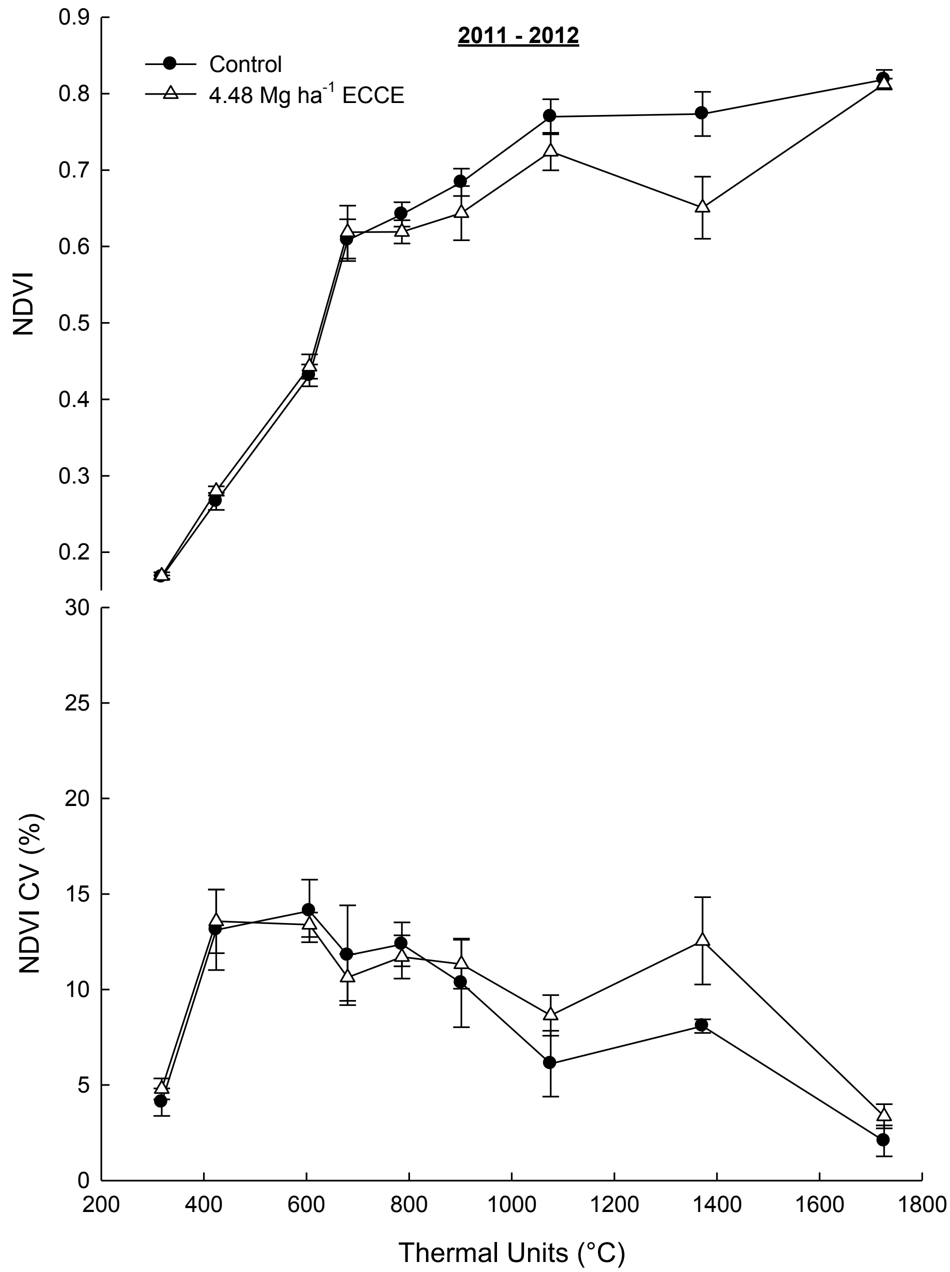


Figure A7. Mean normalized difference vegetative index (NDVI) and coefficient of variation (NDVI CV) from NDVI readings obtained via GreenSeeker sensor by thermal units as a function of treatments with and without lime application in an acid Grant Silt Loam during winter wheat growth stages Feekes 1 to Feekes 5, Waukomis, OK. Vertical bars represents standard deviation.

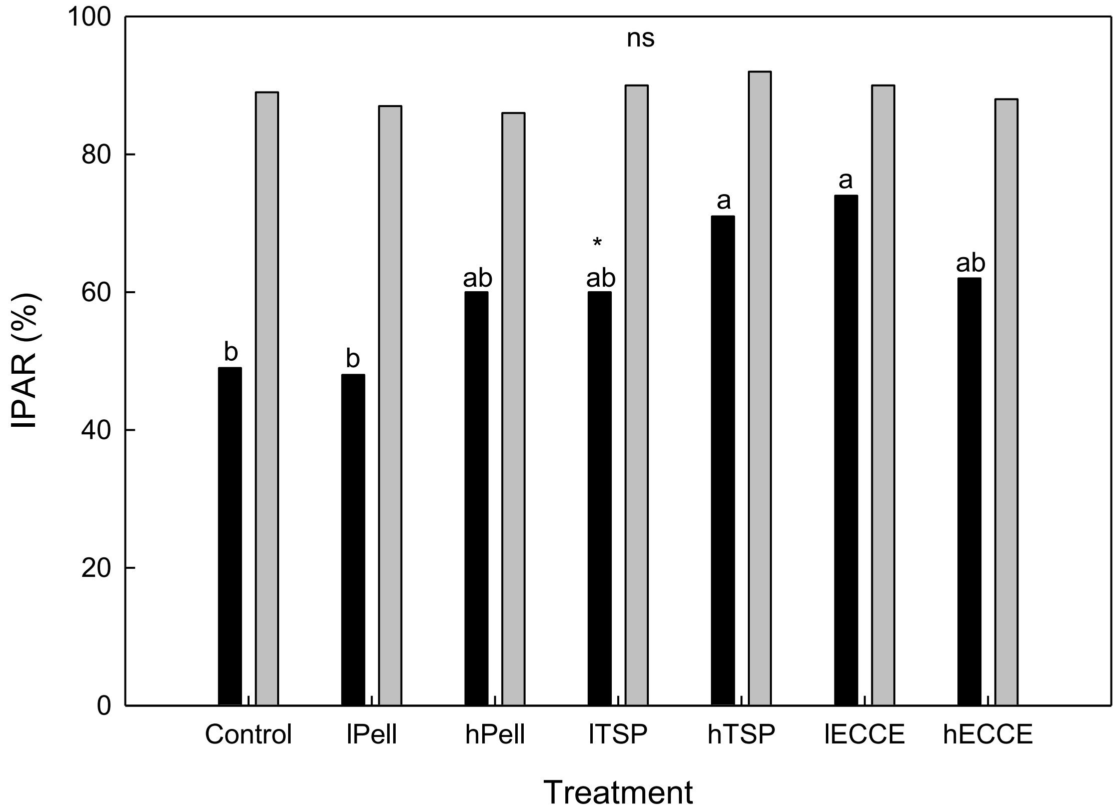


Figure A8. Fraction of intercepted photosynthetic active radiation (IPAR) at heading by winter wheat in 2010 – 2011 (black bars) and 2011 – 2012 (grey bars) as affected by acidity amendment treatment at Waukomis, OK. Control, no amendment strategy adopted; lPell, low rate (224 kg $ha^{-1}$ $yr^{-1}$) in furrow pelletized lime; hPell, high rate (448 kg $ha^{-1}$ $yr^{-1}$) in furrow pelletized lime; lTSP, low rate (28 kg $ha^{-1}$ $yr^{-1}$) triple super phosphate (TSP); hTSP, high rate (56 kg $ha^{-1}$ $yr^{-1}$) in furrow TSP; lECCE, low rate (2.25 Mg $ha^{-1}$) effective calcium carbonate equivalent (ECCE) lime broadcast incorporated; hECCE, high rate (4.50 Mg $ha^{-1}$) ECCE. Identical letters in same-colored columns indicate no statistical difference by the Duncan's test at $\alpha = 0.05$.

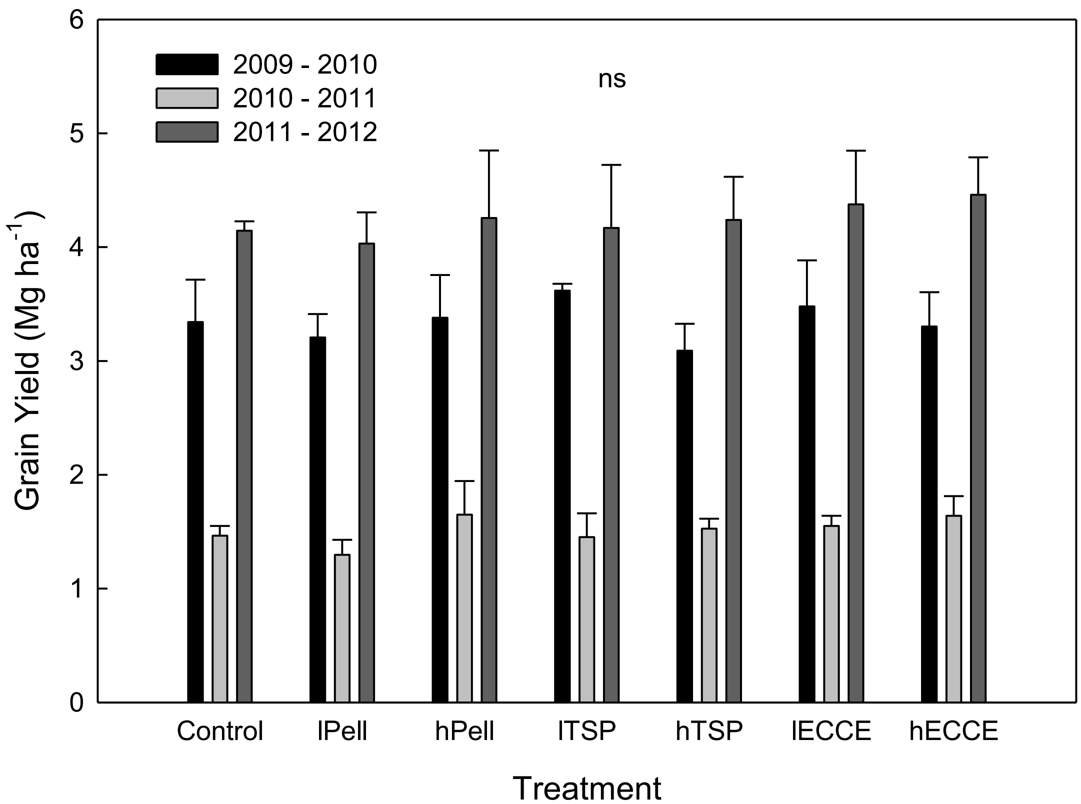


Figure A9. Mean grain yields (Mg ha$^{-1}$) of winter wheat Fuller variety as a function of lime acidity amendment strategy for the growing seasons 2009-2010, 2010-2011, and 2011-2012 in a Grant Silt Loam in Waukomis, OK. Control, no amendment strategy adopted; lPell, low rate (224 kg ha$^{-1}$ yr$^{-1}$) in furrow pelletized lime; hPell, high rate (448 kg ha$^{-1}$ yr$^{-1}$) in furrow pelletized lime; lTSP, low rate (28 kg ha$^{-1}$ yr$^{-1}$) triple super phosphate (TSP); hTSP, high rate (56 kg ha$^{-1}$ yr$^{-1}$) in furrow TSP; lECCE, low rate (2.25 Mg ha$^{-1}$) effective calcium carbonate equivalent (ECCE) lime broadcast incorporated; hECCE, high rate (4.50 Mg ha$^{-1}$) ECCE. Vertical bars indicate standard deviation for comparison between bars of a same growing season.

VITA

Romulo Pisa Lollato

Candidate for the Degree of

Master of Science

Thesis: AGRONOMIC AND ECONOMIC RESPONSE OF HARD RED WINTER WHEAT TO MULTIPLE LIMING AND FERTILIZATION STRATEGIES

Major Field: Plant and Soil Sciences

Biographical:

Education:

Completed the requirements for the Master of Science in Plant and Soil Sciences at Oklahoma State University, Stillwater, Oklahoma. December 2012.

Completed the requirements for the Bachelor of Science in Agronomy at Universidade Estadual de Londrina, Londrina, Parana, Brazil. December 2009.

Experience:

Employed by Cargill S/A as an Agricultural Analyst, Sao Paulo, Sao Paulo, Brazil. August 2009 – July 2010.

Employed by Instituto Agronômico do Paraná (IAPAR) as an intern in the Department of Plant Breeding and Genetics, Londrina, Parana, Brazil. March 2006 – July 2008.

Internship at Instituto Nacional de Tecnología Agropecuaria (INTA) in the Department of Plant Breeding, Cerrilhos, Salta, Argentina. January and February 2008.

Professional Memberships:

American Society of Agronomy 2010 – Present
Crop Science Society of America 2010 – Present
Soil Science Society of America 2010 - Present

Name: Romulo Pisa Lollato Date of Degree: December 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: AGRONOMIC AND ECONOMIC RESPONSE OF HARD RED WINTER WHEAT TO MULTIPLE LIMING AND FERTILIZATION STRATEGIES

Pages in Study: 62 (84 with Appendices) Candidate for the Degree of Master of Science

Major Field: Plant and Soil Sciences

Scope and Method of Study:
Application of agricultural lime is the most frequently recommended method for managing low soil pH; however, in-furrow phosphorus (P) fertilizer or pelletized lime are also commonly used to ameliorate soil acidity. The objectives of this study were to evaluate three soil acidity amendment strategies for winter wheat production. The effects of broadcast agricultural lime (2.25 or 4.50 Mg ECCE ha-1), banded pelletized lime (225 or 450 kg ha-1 yr-1), and banded P fertilizer (28 or 56 kg ha-1 yr-1) on bulk soil pH, aluminum saturation (Alsat), pH change in the soil profile, wheat vegetative development, plant population uniformity, and grain yield, were investigated during three growing seasons in a Grandfield Fine Sandy Loam and a Grant Silt Loam with initial soil pH of 4.8 and 4.9 at Altus and Waukomis, OK.
Findings and Conclusions:
Broadcast agricultural lime at 4.50 Mg ha-1 increased soil pH by one unit and decreased Alsat by 98% at Waukomis. Neither banded pelletized lime nor P fertilizer affected these parameters in either location. Changes in soil pH caused by banded pelletized lime were restricted to the region surrounding the pellet, while broadcast agricultural lime increased soil pH throughout the profile. In-furrow P fertilizer increased vegetative growth and plant population homogeneity in all years of the study at Waukomis; broadcast lime provided similar results in 2010-11 when low soil pH effects on crop growth were more apparent due to severe drought. Wheat grain yield was not affected by treatment, probably due to low soil Alsat. When broadcast lime costs were amortized over five years, 2.25 Mg ECCE ha-1 and the control resulted in the highest net returns among treatments. Results indicate that banded P fertilizer or broadcast agricultural lime can increase early-season wheat growth and population uniformity in a low-pH soil, but this increase in vegetative growth might not result grain yields significantly higher than the control when Alsat is lower than 10%.

ADVISER'S APPROVAL: Dr. Jeffrey T. Edwards